TELEMETRY TRANSDUCER HANDBOOK

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FOREWORD

This Handbook is a revision of the Telemetry Transducer Handbook originally prepared by Radiation Incorporated under U. S. Air Force Contract No. AF 33(616)-7466.* The updating and expansion effort has been performed under U. S. Air Force Contract No. AF 33 (616)-8309, for the Aeronautical Systems Division, Air Force Systems Command. The Air Force Project and Task numbers are 4107 and 410719, respectively. The work was performed under cognizance of the Flight Control Laboratory ** ASRMC -42 and the Air Force Project Engineer, Mr. Paul Polishuk.

The draft of the original handbook was prepared during the seven-month period of 30 June 1960 to 31 January 1961. Changes and final preparation of the reproducible copy were performed during the period 20 March to 28 April 1961 and delivered to the Air Force in May 1961 for printing and distribution.

It was recognized that the Handbook could be improved and maintained current by continued efforts. Work was started in May 1961 to update and expand the Handbook by revising Volume I and adding supplement material to Volume II.

Volume I Revision contains a completely rewritten Section I, Telemetry Systems, resulting from a review of the original Section I by Dr. L. L. Rauch and the rewriting by Mr. Dan McRae. Both are associated with the Advanced Planning Group at Radiation Incorporated. Material was added to Section II, Fundamentals to include acceleration, temperature, vibration, thrust and bio-instrumentation. Section III, Applications, was expanded with information on satellite and space probe instrumentation. Section IV on Transducer Calibration and Test Techniques has additional data on particular test and calibration methods as suggested from manufacturers bulletins and NBS reports. A list of NBS reports and other references are given pertaining to detailed evaluation procedures. It has been difficult to obtain handbook type data to present standardized methods of approach in this area. Facilities available for instrument calibration and test are listed in Section V as received from solicited organizations. A numerical

* This revision supersedes Volume I of WADD-TR-61-67 dated July 1961.
**Presently designated Flight Control Division of the AF Flight Dynamics Laboratory.

listing of references is included in Section VI and a comprehensive Bibliography with indexing constitute Section VII. Section VIII, Appendixes, contains miscellaneous material, details, and derivations pertaining to material in Sections I, II, III, and IV.

The updating and expansion of Volume II of the handbook have been accomplished through the preparation of three separate supplements, presenting new material for insertion in the original Volume II. Supplement 1 contained 100 additional transducer data sheets, a revised manufacturer's listing and additional transducer research and development information. The final reproducible copy of Supplement 1 was delivered to the Air Force in December 1961. A second supplement was completed and delivered to the Air Force in March 1962 containing 99 additional data sheets, revised manufacturer's listing and further R & D listings, plus an index to the original Volume II and Supplement 1 data sheets. Supplement 3 is being delivered at the same time as the completed revision of Volume I, in May 1962.

Writing, compilation, and editing of the original Volume I was performed by C. O. Alford, L. R. Bauer, J. T. Conklin, R. H. Dimond, G. D. Falcon, H. C. May, L. F. O'Kelley and L. C. Thompson. The bulk of the typing was done by Mrs. Jeanette Thomas. Art work and other preparation of reproducible copy was done by R. K. Hoefler, E. H. Hurlebaus, L. C. Newman, and R. A. Norris. The major portion of proof reading was performed by J. L. Adams. L. F. O' Kelley was the Project Engineer.

The revision of the handbook has been performed in the Data Systems Division at Radiation Incorporated by Mr. H. F. Fisher, Jr., Project Engineer. Mrs. R. E. French and Miss Donna Valentine have been responsible for the typing, handling of correspondence, and maintaining records and files pertaining to the Handbook revision. The art work and preparation of reproducible material and draft copies have been done by Mr. G. E. Roberts and the publications department at Radiation.

Neither Radiation Incorporated nor the U. S. Government in any way endorses the products or services described in this Handbook, or condemn any such that are omitted. In addition the expression of opinions, implied or otherwise, contained

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ACKNOWLEDGMENTS

In the preparation of the original Handbook and the revision, the help and cooperation from transducer manufacturers, user organizations and other government groups have made it possible to perform planned tasks. In most instances references are included as footnotes and in a list of references (Section VI, Volume I). The listing of all contributors of material for use in the Handbook (including the revision) would be too lengthy for inclusion in these pages of acknowledgements, however, the very helpful contributions and assistance of certain individuals and organizations justify the following specific acknowledgments:

Mr. Paul Polishuk for his able guidance and direction as Project Engineer for the Air Force.

Members of the Transducer Committee of the Telemetry Working Group, Inter-Range Instrumentation Group (IRIG), for their creative suggestions at the beginning of the Handbook program and subsequent contributions, including the Glossary of Telemetry Transducer Terms. Committee members are listed as follows:

Mr. Arnold E. Bentz
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In addition, the Telemetry Working Group of the IRIG provided telemetry standards which are included as an appendix to Volume I.

Personnel of the National Bureau of Standards, Washington, D.C.; specifically, Mr. Paul Lederer, Mr. Arnold Wexler, and Mr. Arthur Schach. Mr. Lederer submitted data and photographs related to transducer calibration and reviewed the Handbook draft. Mr. Wexler also reviewed the draft and provided significant recommendations for its improvement. Mr. Schach provided the numerous tables which describe the NBS calibration facilities, reviewed proof copies and recommended certain changes to improve their presentation in the Handbook.

Mr. Joseph Pearlstein of the Diamond Ordnance Fuze Laboratories, Washington, D.C., was very helpful through his consultations with project personnel regarding sources of data, bibliography organization, and the contribution of data for use in the Handbook.

Mr. Harry N. Norton, of General Dynamical Astronautics, San Diego, California, as Chairman of the ISA Survey Committee on Transducers for Aero-Space Testing, submitted significant comments and suggestions during the Handbook's preparation. The cooperation and exchange of information from ISA has been helpful, thanks to Mr. Covey, (former editor) and Mr. Minnar, Editor ISA Journal.

Mr. Malcomb Johnson of the Bendix Corporation, Research Laboratories Division, Southfield (Detroit), Michigan was most cooperative in exchanging information related to transducer manufacturer's survey and questionnaire information concerning nuclear and penetrating radiation environments.

A portion of the text on testing and calibration was contributed by Mr. R. D. Bronson, Convair, Fort Worth, Texas.

U.S. Government organizations which submitted data for either direct or indirect use in the Handbook are listed as follows:

Air Force Flight Test Center
Edwards Air Force Base
California

Air Force Systems Command
Air Research and Development Command
Washington, D. C.

Arnold Engineering Development Center
U. S. Air Force
Arnold Air Force Station
Tennessee

Dayton Air Force Depot
Calibration Standards Division
Gentile Air Force Station
Dayton, Ohio

National Aeronautics and Space Administration
Langley Research Center
Langley Field, Virginia

U. S. Naval Air Test Center
Patuxent River
Maryland

U. S. Naval Missile Center
Point Mugu, California

U. S. Naval Ordnance Test Station
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Radiation Incorporated and the U. S. Air Force are particularly grateful to the many companies which cooperated

in this endeavor by submitting data, photographs and drawings pertaining to transducer fundamentals, testing and calibration facilities, research and development programs, and the catalog of transducers.

ABSTRACT

As a result of studies conducted by the Air Force and others it became apparent that there was a need for a comprehensive collection of data on telemetry transducers. The Telemetry Transducer Handbook has been prepared in an effort to present information and data useful to the transducer user. The material has been prepared in two volumes with general instrumentation information in Volume I and detailed transducer specification data in Volume II.

Volume I consists of technical information on telemetry systems, transducer fundamentals, applications, testing and calibration techniques and facilities. Volume II consists of a listing of transducer manufacturers, complete data (with photographs and outline drawings) on several hundred transducers (over 700 with Supplements 1, 2, and 3), descriptions of transducer research and development programs and an index to the instrument data sheets.

Section I of Volume I discusses in detail the characteristics of the transmission system and its relation to transducers and telemetry systems. References 1 through 119 pertain to Section I discussion offering a guide to more specialized investigation of the many aspects of telemetry systems. Section II covers the fundamentals involved in various physical measurements and how these fundamentals are employed in the general design of transducers. Measurements of displacement, strain, pressure, fluid flow, rotary speed, fuel quantity, ac power, acceleration, temperature, shock and vibration and thrust are discussed. Section III offers general information and examples in the application of telemetry transducers. Testing and calibration techniques and facilities available are presented in Sections IV and V. A list of performance reports available from NBS offers some evaluation information on telemetry transducers.

The List of References, Section VI, groups all references cited in Sections I - V in the numerical order of their appearance in the text. An extensive bibliography is presented in Section VII. There are 835 listings. An index to the bibliography is also included. Appendix material is included in Section VIII. There is a glossary of terms, IRIG Telemetry Standards definitions of many basic physical effects and principles related to transducer design, and detailed data on acceleration, temperature and thrust measurement fundamentals.

The Table of Contents in Volume I also includes Volume II Contents. This includes all material in the original Volume II plus Supplements 1, 2, and 3.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

H. W. BASHAM
Chief, Control Elements
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SECTION I

TELEMETRY SYSTEMS

1-1 INTRODUCTION

The word "telemeter" is derived from the Greek words "tele" which means "far" and "metron" which means "measure." Thus telemetry is the art of measuring from afar.

Although almost any measurement apparatus or communication system might be called a telemetry system dependent upon ones interpretation of "measure" and "far," this section is concerned principally with telemetry systems used to monitor parameters associated with aircraft, missiles, and space vehicles. At least to date, the bulk of the output of the telemetering industry in the United States is used in this connection. Industrial applications such as remote monitoring by electrical utility and oil companies and other scientific applications such as oceanography, hydrography, and physiological measurements will be discussed briefly.

The telemetry system can be divided functionally into three parts. (Figure 1-1) These are:

1) The transducers - which are located at the remote station and transform the physical quantities to be monitored into electrical signals.

2) The transmission system - which consists of: a device for transforming the electrical signals from the transducers into one suitable for transmission to the receiving station (remote processor); the transmission and receiving devices; and device for transforming the output of the receiver to forms suitable for display and interpretation (receiving processor).

3) The display and interpretation system - which consists of the devices which calculate the desired parameter and display them for final interpretation by automatic or human means.

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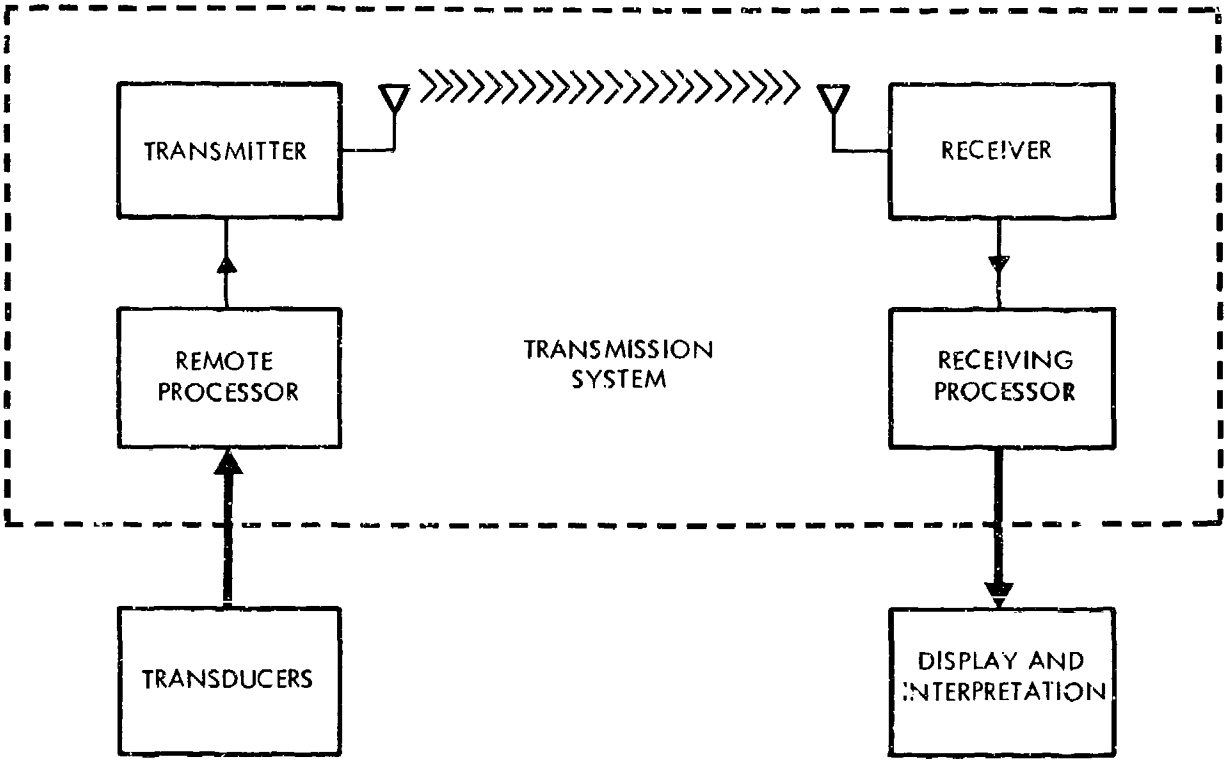


Figure 1-1 Functional Diagram

In the broadest (and most realistic) sense, the purpose of the telemetry system is to provide data in such a form that the interpretation of this data will lead to correct decisions concerning the remote quantities or devices which are monitored. Therefore, the transducer must be considered by the systems engineer as a part of the telemetry system. Of equal importance, the transmission system must be considered by the measurement engineer as a part of the measurement device. For this reason the first section of the "Telemetry Transducer Handbook" will be devoted to a general discussion of the transmission system and its relationship to the over-all measurement problem.

1-2 SELECTION OF TRANSMISSION SYSTEM CHARACTERISTICS

As was stated in the preceding paragraph, the purpose of a telemetry system is to monitor remote occurrences so that correct decisions can be made concerning the physical quantities or devices associated with those occurrences. The variety of measurement problems, however, have thus far precluded attempts to relate in a general sense the characteristics of the transmission system with the ability to make correct decisions. Therefore, the selection of transmission system characteristics has usually been divided into two steps:

1) Selection of the measurements and transducers; and evaluation of the characteristics of the data which may be expected from the transducers and the accuracy which must be maintained by the transmission system.

2) Selection of the transmission system characteristics based upon cost in terms of power consumption, spectral occupancy, size, weight, reliability and dollars. These are functions of the data characteristics and accuracies required.

As can be imagined, both of the two steps mentioned above are quite complex involving many considerations which are special to the particular use envisioned for the telemetry system. Therefore, a single all encompassing equation is not available which allows satisfactory determination of system parameters in a

completely straightforward fashion. Rather, the system parameters must be chosen on the basis of the theoretical relationships between system parameters which are available to the chooser, upon his knowledge of available hardware, and upon his past experience, after thorough consideration has been given to the purpose of the over-all telemetry system. This is true whether the system envisioned is to be specialized or "general purpose" since the two differ only in degree of specialization.

There has been much analysis done in the area of relating the required transmitter power, the spectral occupancy, the transmission system characteristics (including type of transmission system and adjustment of internal parameters within the system) and the accuracy required of the data (Ref. 1 through 60). For the most part the analyses have been based upon idealistic assumptions of the data characteristics (data with spectral characteristics corresponding to band limited white noise). Idealized filter characteristics have also been assumed in many of the analyses. Although these analyses have necessarily made approximations they represent an important tool to system designers since they deal with some of the most definitive and complex relationships involved in selection of system parameters.

It is not feasible to present transmission system analysis in this section since they belong more properly in a book on the subject. Instead, a discussion of the different techniques available to the telemetry user will be presented. This will be done in two steps. The first part will describe the principle of operation of the various techniques and discuss from a general point of view the principal considerations involved in the use of each technique. The second part will discuss specific cases of past applications of the techniques. Throughout, an attempt has been made to include sufficient references so that the reader with more specialized interest can investigate his problem in greater depth if he so desires. Due to the large number of references used in this section the references are collected and listed numerically in Section VI.

1-3 TRANSMISSION SYSTEM FUNDAMENTALS

a. Multiplexing

In most telemetry applications, it is desired to perform a number of different measurements. Although, a separate transmission link could be used for each measurement, the problems of

cost in terms of power, spectral occupancy, weight, size and dollars normally precludes this possibility. Therefore, it is common to send many measurements over a single transmission link. This process is called multiplexing.

There are two types of multiplexing in common use today. These are:

1) Frequency division multiplexing

2) Time-division multiplexing

These techniques will be discussed in more detail below.

b. Frequency Division Multiplexing

The basic operation of a frequency division multiplex system is illustrated in Figure 1-2. The measurement signals from the transducers are used to modulate "subcarrier" oscillators tuned to different frequencies. The outputs of the subcarrier oscillators are then linearly summed in voltage and the resulting composite signal used to modulate the prime transmitter. At the receiving site the composite signal is obtained from the receiver demodulator and fed to a number of band-pass filters which are tuned to the center frequencies of the subcarrier oscillators. The outputs of these filters are then demodulated to obtain the individual measurement signals. Thus in frequency division multiplex systems, the individual measurements are transmitted in such a form that they occupy different regions of the video or baseband frequency spectrum.

All types of modulation can be used for both the subcarrier oscillators and the prime carrier; that is: frequency modulation (FM), phase modulation (PM), amplitude modulation (AM), suppressed carrier amplitude modulation (SC) and single sideband amplitude modulation (SS). Frequency division multiplex systems are normally designated by listing the type of modulation used for the subcarriers followed by the type of modulation used for the prime carrier. Thus FM/AM would indicate a frequency division multiplex system in which the subcarriers are frequency modulated by the measurement and the prime carrier is amplitude modulated by the composite subcarrier signals. Almost all combinations of sub- and prime-carrier modulation techniques have been used in the past. However,

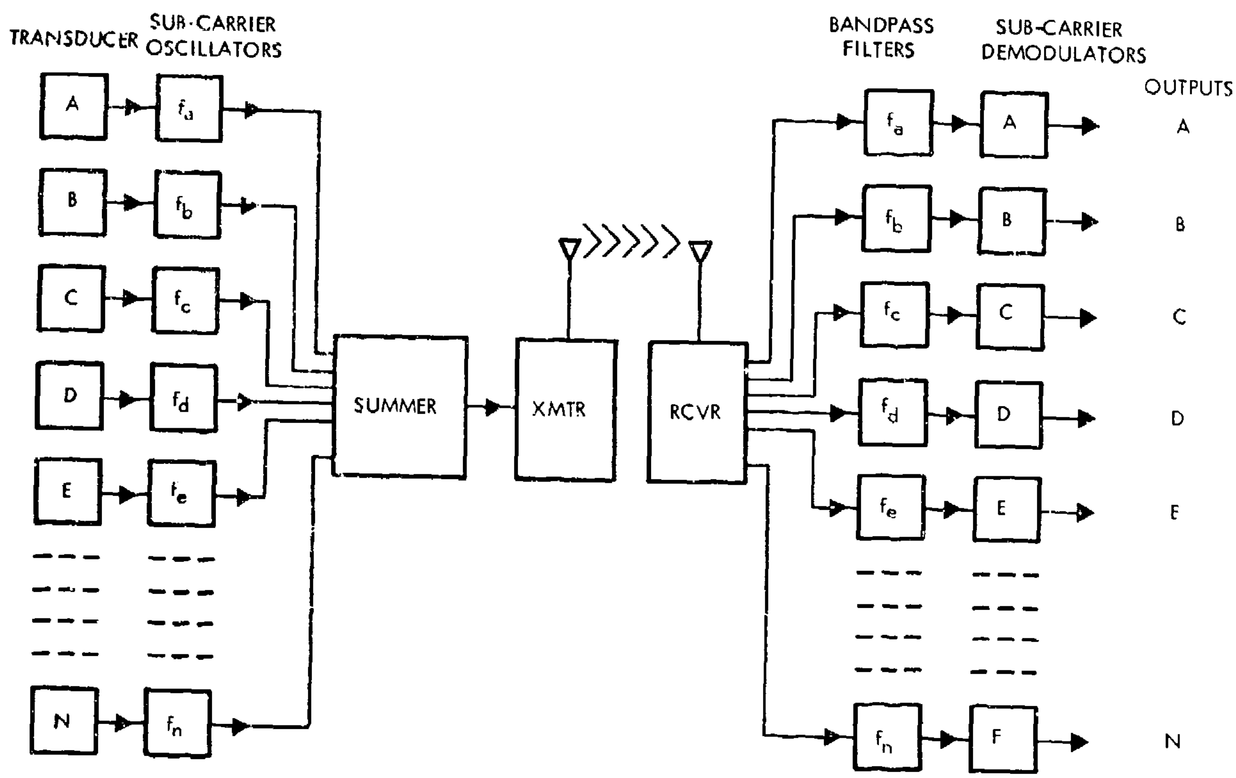


Figure 1-2 Frequency Division Multiplexed System

FM/FM is by far the most common technique in use today.

The principal sources of errors in a frequency division multiplex transmission system are:

1) Drifts

2) Bandlimiting

3) Cross Talk

4) Distortion

5) RF Link Noise

The most objectionable drifts are those associated with modulation and demodulation of the subcarriers. If the drifts are slow their effect can be greatly diminished by use of calibration signals. The errors due to drifts are not fundamental to the system and hence their magnitude depends upon the ability of the circuit designer. For the purposes of this report errors of this type will be called systematic errors.

Errors due to bandlimiting occur throughout the system wherever the data is dynamic in nature (as is all data except the trivial case of dc). The amount of error caused by bandlimiting is a direct function of the spectral characteristics of the data and the amount of spectrum which is to be allocated to the telemetry system. Hence, this type of error is fundamental to the system in that for a fixed type of data (non-ideal) and spectrum allocation (finite) the error cannot be eliminated regardless of the circuit design. The errors due to bandlimiting are most severe when the bandlimiting takes place directly on the data; that is: prior to modulation or after demodulation of the subcarrier. Bandlimiting of the modulated subcarrier signals either in the subcarrier oscillators or in the band-pass filters at the receiving station also can cause objectionable error unless care is taken. The bandlimiting of the modulated prime carrier in the transmitter or receiver i-f is of less bother but cannot be ignored completely. In practical systems the bandlimiting errors may be at least as dependent on the phase linearity of the filters involved as they are on amplitude roll-off.

Cross-talk errors in frequency decision multiplex systems are of two varieties, one which is systematic and one which is fundamental. The first of these is caused by non-linearities in the summing amplifier prior to the transmitter or in the modulation or demodulation process of the prime carrier. Non-linearities at these points in the system cause production of frequency components in the video or base-band spectrum that would not otherwise be present. If these additional components lie in a frequency range which is passed by the band-pass filters at the receiving station, they will appear at the outputs of those channels as errors. Since in theory no limit exists on the linearity which can be achieved, these errors are systematic. The second type of cross-talk errors are those due to overlap in the baseband spectral content of the information channels. Since non-idealistic data spectra contain tails which die off but do not go to zero, there will always be some overlap which passes through band-pass filters adjacent in frequency and causes error in those channels. The amount of error from this source is dependent upon the frequency spacing between the sub-carrier channels and the nature of the data and hence is fundamental to the system.

Distortion error is error due to non-linearities in the subcarrier modulator and demodulator (not to be confused with cross-talk errors due to non-linearities in the prime carrier modulator and demodulator). As in the case of drift, errors due to distortion at this point in the system can be alleviated somewhat by use of calibration signals. This class of error is systematic.

The RF link noise causes errors which are random in nature but are fundamental to the system since their magnitude depends upon almost all of the transmission system parameters. The principal contributors to this noise are: the receiving station front end, galactic sources and man-made interference.

Although the sources of error which have been discussed should normally represent the principal ones of the frequency division transmission system, others can be of significance when the transducer outputs are low level. In these cases amplifiers are normally used between the transducers and the subcarrier modulator. In such cases the random noise contributed by the first stage of the amplifier, errors due to common mode signals on the transducer lines, and errors due to electrical pickup can be significant. The analytical

treatments contained in references 1-23 deal with frequency division systems.

c. Time-Division Multiplex Systems

The operation of a time-division multiplex system from a functional standpoint is illustrated in Figure 1-3. The signals from the transducers are fed to a commutating device which samples the channels sequentially. Thus, the output of the commutator (also referred to as the multiplexer) is a series of pulses, the amplitudes of which correspond to the sampled values of the input channels from the the transducers. This train of pulses is then passed through a device which converts it to a form suitable for modulating the transmitter. At the receiving station the process is reversed. The demodulated output from the receivers is passed through a converter which reproduces the pulse train that existed following the commutator at the transmission site. This pulse train can then be decommutated to produce pulses with values corresponding to samples of the original measurement signals. In many cases, interest in the value of the measurement cannot be guaranteed to coincide with time at which a sample is available. In such cases it is then necessary to interpolate in some fashion between samples. The interpolation process may also be used to produce a continuous time waveform from the sampled values.

As was the case in frequency division systems the modulation of the transmitter may take any form, that is AM, FM, PM, etc. However, the principal distinction between time-division systems lies in the form of the converter. In this regard the types of systems can be divided into two broad categories:

1) Analog Systems

2) Digital Systems

The analog systems are those in which the output of the converter varies continuously in some fashion, or in other words is an analog of the input voltage to the converter. In the digital systems, however, the converter is capable of putting out only a discrete number of waveforms, although the input voltage may vary continuously. Thus, the principal distinction between analog and digital systems lies in whether the modulation waveform can be varied continuously in some fashion, or can take only discrete values. In this respect, all of the frequency division systems discussed

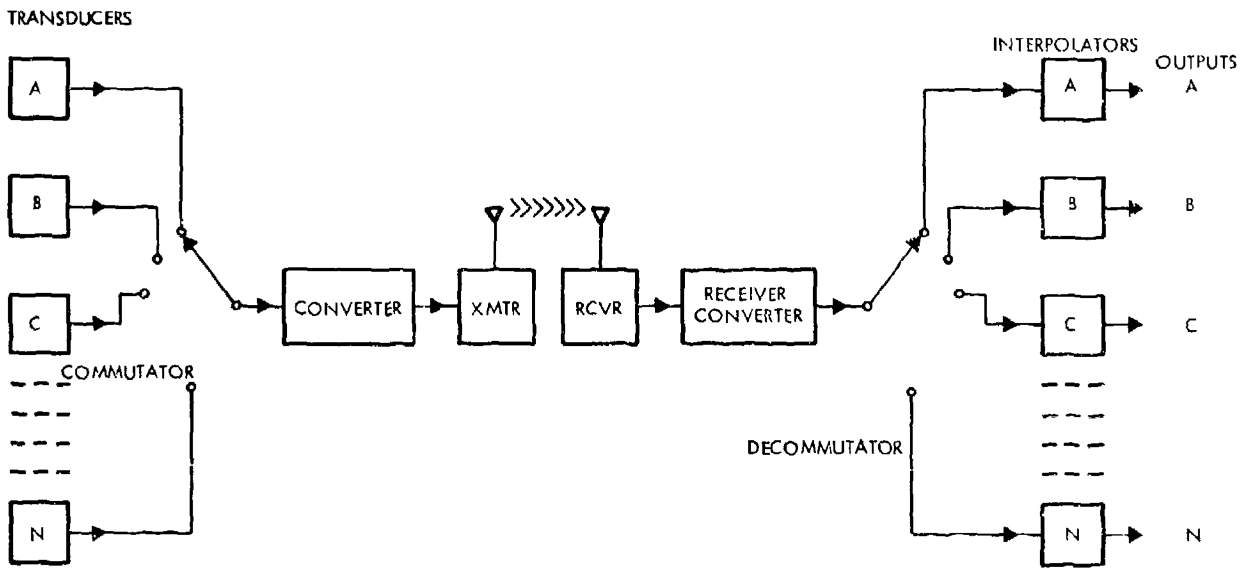


Figure 1-3 Time Division Multiplexed System

previously are considered to be analog systems. Since the properties of the analog and digital time-division systems are somewhat different we will present first the principle of operation of the major analog time division techniques followed by a discussion of the principal sources of error in these systems and then follow with a similar discussion of the digital time-division systems.

(1) Analog Time-Division Systems

The primary analog time-division multiplexed systems in use today are:

1) Pulse amplitude modulation (PAM)

2) Pulse duration or width modulation (PDM) or (PWM)

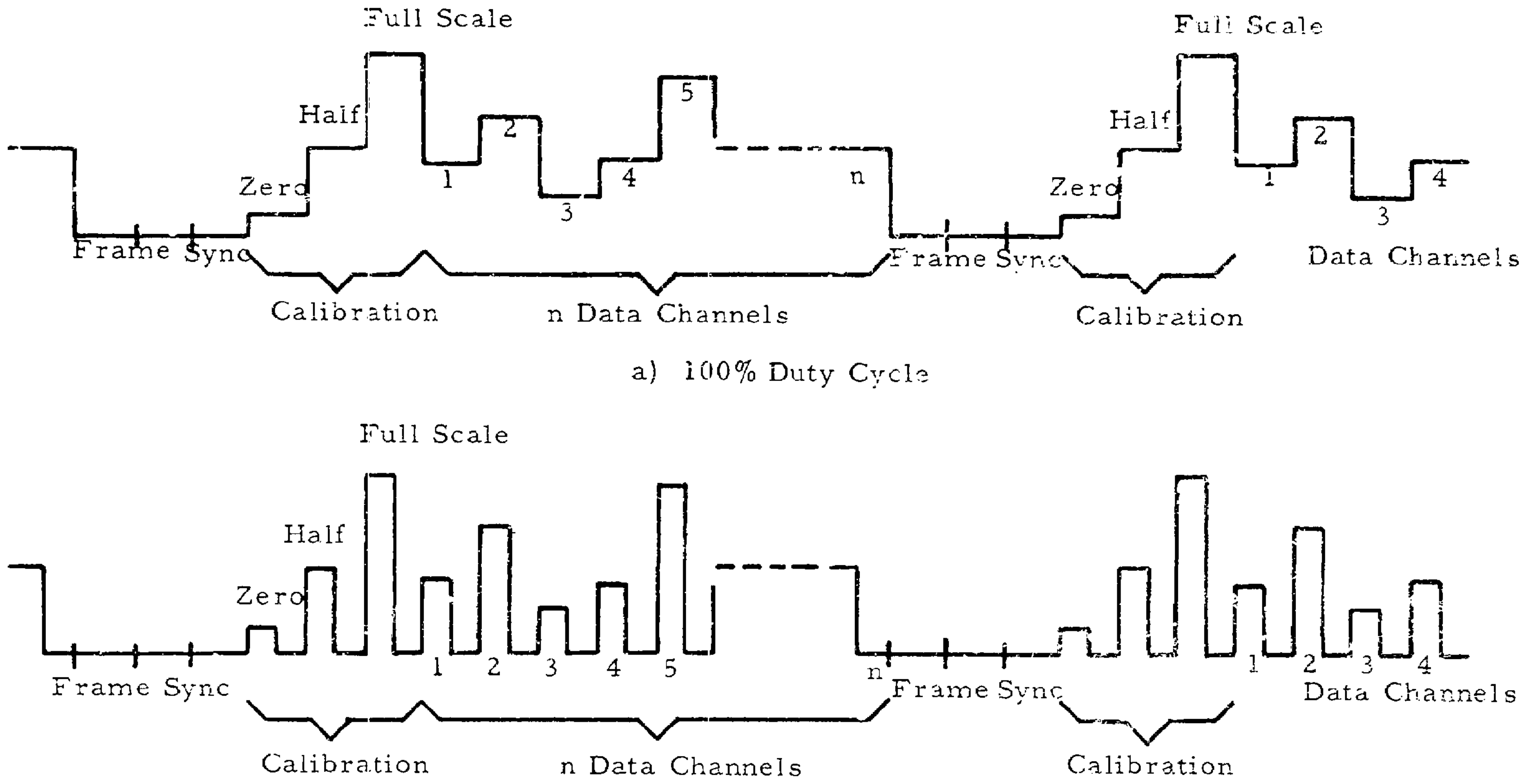
3) Pulse position or time modulation (PPM or PTM)

As has been mentioned any of these techniques can be used to modulate the prime carrier in any fashion. The system designation normally lists the type of converter first followed by the type of prime carrier modualtion. That is PDM/PM would be a pulse duration type converter, the output of which is used to phase modulate the prime carrier.

(a) Pulse Amplitude Modulation (PAM)

A pulse amplitude modulation system is one in which the output of the commutator is used directly to modulate the prime transmitter. Thus the converter is simply a pair of wires. Hence PAM is the simplest time-division multiplex system. Indeed PAM wavetrains are produced as the first step in virtually all time-division multiplex systems.

The pulse amplitude wave trains may take several forms, two of which are illustrated in Figure 1-4. The principal difference lies in the duty cycle system. The length of time necessary to sample all channels is normally referred to as a frame time. In order to be able to identify the sample at the receiving station it is necessary to insert frame synchronization.



a) 100% Duty Cycle

b) 50% Duty Cycle

Fig. 1-4 Pulse Amplitude Waveform

Several different methods can be used to designate frame. The one illustrated in Figure 1-4 consists of forcing several consecutive channels to a level below the minimum allowable data value. Since drifts and non-linearities in the system cause error directly, it is also common to transmit calibration pulses as shown. The data is offset in such a fashion that channels with signal outputs which are capable of both positive and negative polarities are centered about the half scale value.

Figure 1-4b illustrates a 50% duty cycle PAM wavetrain. As in the case of the 100% duty cycle wavetrain the frame synchronization for 50% duty cycle is designated by several consecutive channels returned to a reference level which is also returned to this level during half of each channel time.

The 50% duty cycle wavetrain has been used to a greater extent in the past due to the relative ease of synchronizing at the receiving station. In general the 100% duty cycle system occupies a smaller spectrum than that of the 50% duty cycle system. Also a longer time period is available for filters in the system to reach the full pulse height. However, the dead time available in the 50% duty cycle system allows the use of circuitry to dump the transients in the storage devices of the video filter hence reducing crosstalk between successive channels.

(b) Pulse Duration Modulation (PDM)

Pulse duration modulation is a time-division multiplexed technique wherein the duration of pulses is varied in proportion to the modulation signal. The pulse train, then, consists of a string of pulses with different widths as illustrated in Figure 1-5. Guard time is allowed at both the beginning and the end of each pulse to reduce the difficulties associated with interchannel crosstalk. Since the information is carried in terms of pulse width, drifts and non-linearities in the system do not have as great an effect upon data accuracy as they do in an equivalent PAM system. PDM systems are analog in nature, however, since the pulse duration is varied continuously rather discretely. Thus RF link noise and interference as well as system transients introduced by band limiting directly affect the accuracy of the data.

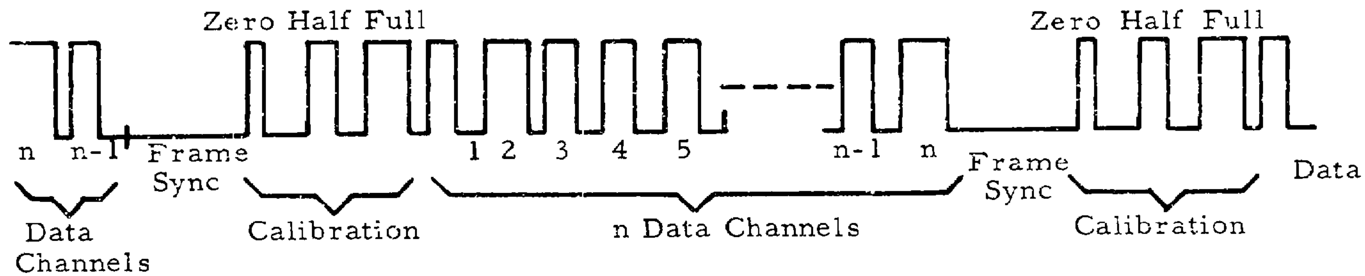


Fig. 1-5 Pulse Duration Waveform

(c) Pulse Position Modulation (PPM)

Pulse position modulation is similar to pulse duration modulation except that rather than using the entire duration of the pulse, only the trailing edge of the pulses are transmitted to identify the pulse width. It is used principally in conjunction with an amplitude modulated prime carrier since its principal advantage lies in the small percentage of time that pulses are present, thus allowing relatively high peak powers and low average powers. The wider system bandwidths required (as compared to PDM and PAM) makes its use in conjunction with a frequency modulated prime carrier undesirable, since the reduction in average power for the FM system could not be realized.

A typical pulse position waveform is shown in Figure 1-6 along with the equivalent pulse duration waveform. The synchronization pulses shown also may vary from system to system. Although pulses corresponding to the leading edge are not transmitted in the system illustrated this may be done to reduce synchronization problems at the receiving station.

(d) Errors in Analog Time-Division Multiplex Systems

The principal sources of error in analog time-division multiplex systems are closely related to those in frequency division multiplex systems. These are:

1) Drift and non-linearity
2) Bandlimiting
3) Crosstalk
4) Interpolation errors
5) RF link noise

With the exception of pulse amplitude modulation, only drifts and non-linearities associated with equipment prior to (and including) the remote converters and after (and including) the receiver converter are of primary concern to analog time division systems. As is the case in the frequency division systems this drift and non-linearity is systematic in that the amount is dependent entirely on the state-of-the-art in circuit design, and calibration signals can be of considerable aid.

Errors classified as bandlimiting errors in time-division systems are produced only in the equipment preceding the multiplexer. Errors due to bandwidth restrictions in other parts of the system are usually classified under different names. Since, in theory, there is no reason to bandlimit the system at this point, these errors are also

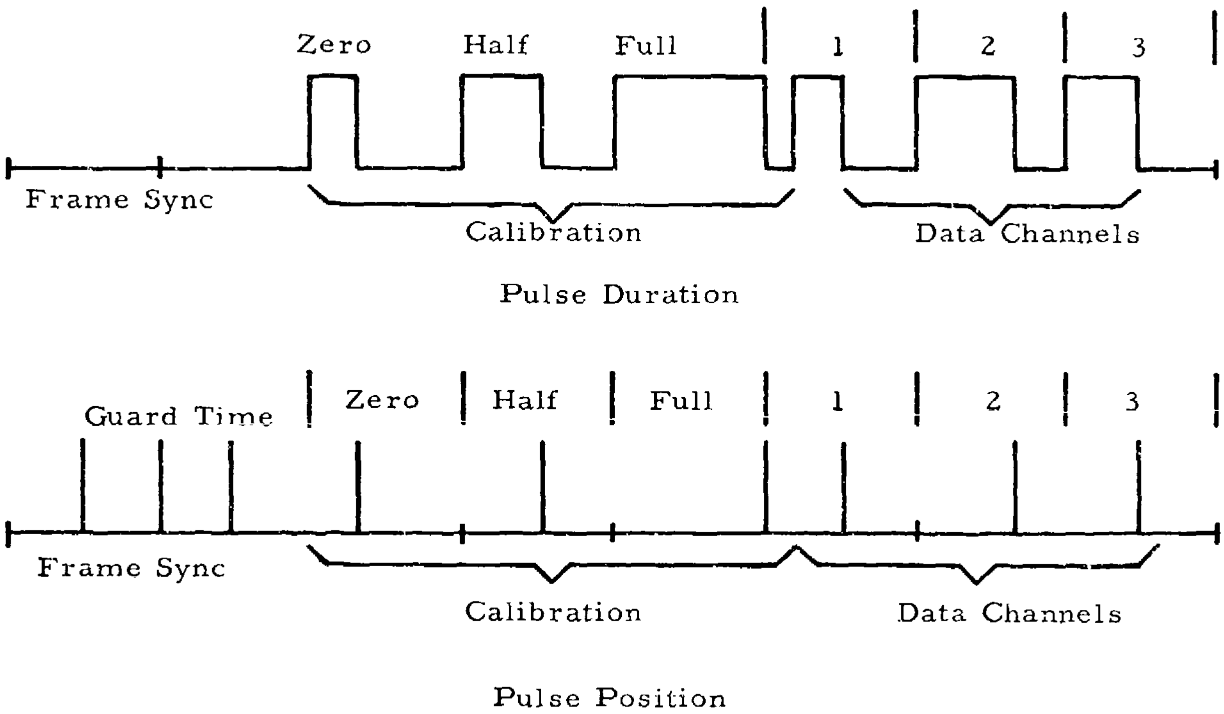


Fig. 1-6 Pulse Position Waveform

systematic in nature and depend upon the phase and amplitude response of the filters involved as well as the character of the data.

Crosstalk in a time-division system normally occurs from bandlimiting of the pulse video signal causing transients from channel pulses to effect the pulses of the channels following. The relationship between bandlimiting and crosstalk varies from system to system. There is no crosstalk due to non-linearity in time-division systems. Crosstalk in a time-division system is a fundamental error.

Interpolation error comes about when an attempt is made to reconstruct a continuous waveform from the sampled values of the original waveform available to the receiving station. The amount of interpolation error is a function of the characteristic of the data which was sampled, the method of interpolation and the sampling rate and, hence, is a fundamental error in the system. The power spectrum of a waveform consisting of impulse samples of a continuous waveform is made up of images of the spectrum of the original waveform (Figure 1-7). The purpose of the interpolation process is to recover intact the image appearing about dc while ignoring frequency content belonging to other images (which appear about the sampling frequency and its harmonics). Normally, the interpolation process is such that it introduces distortion due to bandlimiting in the spectrum about zero frequency and allows some content of the unwanted images into the output. These two types of error have been termed errors of omission and errors of commission respectively. The errors of commission are also called foldover errors and aliasing errors. It should be noted that errors of omission are almost directly equivalent to errors due to bandlimiting in the subcarrier bandpass filters of frequency division systems. Also errors of commission are almost directly equivalent to errors due to adjacent channel crosstalk in frequency division systems. Thus the fundamental relationships imposed on system parameters by fixing interpolation error in a time-division system has almost a direct counterpart in frequency division systems.

The RF link errors, as in the frequency division system, are fundamental being functions of the received signal power at the receiving station and many other system parameters.

As was the case in frequency division systems additional errors not listed can occur when the measurement device output is at low level. The amount of error varies dependent upon whether a separate amplifier is to be supplied for each channel prior to commutating or whether the commutating or multiplexing is to be done at low level. Until fairly recently it was not considered feasible to perform low level commutation in systems with missile environment. References 1-9 and 26-36 consider various aspects of time division systems. References 32-36 consider specifically the interpolation problem.

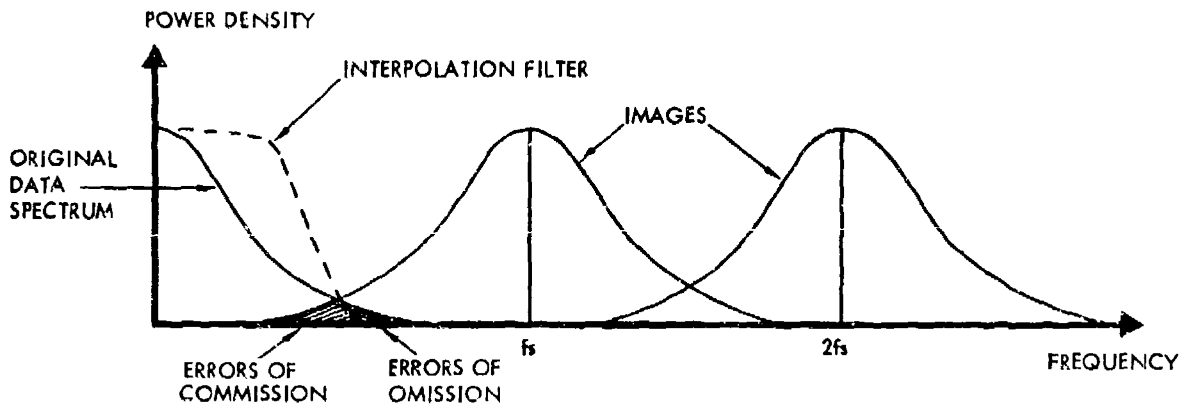


Figure 1-7 Power Density Spectrum of Sampled Data Waveform

(2) Digital Systems

The output of the converter in a digital system can take on only certain discrete forms. Each of the possible outputs of the converter can be thought of as a separate message. If the input to the converter is a continuously variable voltage, such as would be the case in many measurement problems, it is common to divide the range of probable variation into segments of voltage. The converter has an output waveform assigned to each segment and is constructed such that it supplies the output corresponding to the segment occupied by the input waveform. The process of segmenting the input range of variation is known as quantizing and the segments themselves are referred to as quantization levels. The converter output is usually called a code and the converter itself either a coder or analog to digital converter (A to D converter).

As may be imagined an unlimited number of different types of digital systems could be envisioned since an unlimited number of different code waveforms are available. However, a large majority of digital telemetry systems use a code which is made up of pulses which are weighted in a binary fashion. The interval of time allotted for each pulse is quite often referred to as a bit time (in teletype this is called a baud time). The codes are distinguishable from one another by the presence or absence of the pulses. Thus the waveform in each bit position can take on one of two possible configurations. Codes of this variety will be called two-level codes herein to avoid confusion with the binary weighting of the individual bits which will be discussed in the following section. Along this line it is worth noting that quite often in literature the word binary is used interchangeably to describe either or both of these properties of the code (that is: number of levels and weighting) and hence one needs to take care in its interpretation. Codes with binary weighting of the bit values are invariably two level codes. However, the converse is by no means true.

The discussion of digital systems will be divided into four sections. The first will concern the binary, two-level, pulse coding mentioned above. The next section will discuss a different variety of two-level pulse coding known as orthogonal coding. The third section will discuss briefly other forms of coding. Lastly, the principal sources of error in digital systems will be presented. All of the digital systems discussed in this section are of necessity time-division multiplexed systems.

(a) Binary Pulse Code Modulation (PCM)

Two-level, binary weighted, pulse coded systems have been used to such an extent in the past that the abbreviation for pulse code modulation (PCM) has been quite often used to imply a system of this type*. The weighting of the codes are illustrated in Figure 1-8. As can be seen, the code which stands for each quantizing interval is represented by a sequence of bit intervals which are distinguished by the presence or absence of a pulse. The weighting assigned to each bit interval is a binary number. The total value of the code can be obtained by adding up the weighting values of all bits with pulses present (this can also be thought of as multiplying the weighting assignments by "zero" or "one" depending on the absence or presence of pulses, and summing the results). The code illustrated is a three bit code which has eight possible values. The number of values or quantizing levels which can be represented by a sequence of n bits weighted in binary fashion is 2^n.

Figure 1-9 illustrates the entire coding procedure where a three bit code (eight quantizing levels) is again used to simplify the illustration. The zero to full scale range of the input analog signal is divided into quantizing segments as shown and the quantizing segments numbered. The samples of the analog waveform are coded corresponding to the quantizing interval occupied by the sampled value.

Thus far the transmission of "one" or "zero" value during a bit interval has been referred to as being designated by the presence or absence of a pulse. In actual practice this waveform can take on many different forms. Figure 1-10 shows a number of the different waveforms which can be used. The non-return-to-zero waveform is probably the most commonly used of those shown. However, all of those shown have either been used in systems to date or are to be used. When the non-return-to-zero or return-to-zero waveforms are used it is common practice to use a pre-modulation filter to round off the corners of the modulating waveform.

*Strictly speaking, however, a system of pulses which can take on four levels rather than two and has weighting of bits other than binary should also be considered a pulse code modulation system.

Fig. 1-8. Decimal and Binary Equipment

Decimal	Binary Code	Pulse * Group
0	000	
1	001	
2	010	
3	011	
4	100	
5	101	
6	110	
7	111	

* Dashed line represents absence of pulse

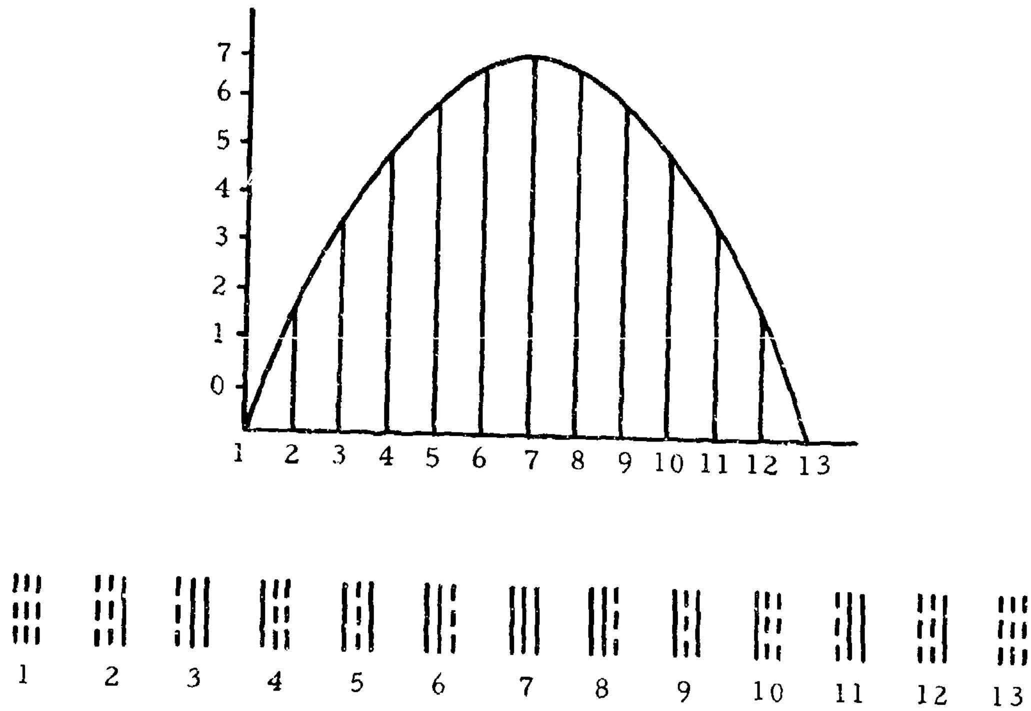


Fig. 1-9. Illustration of Pulse Coding

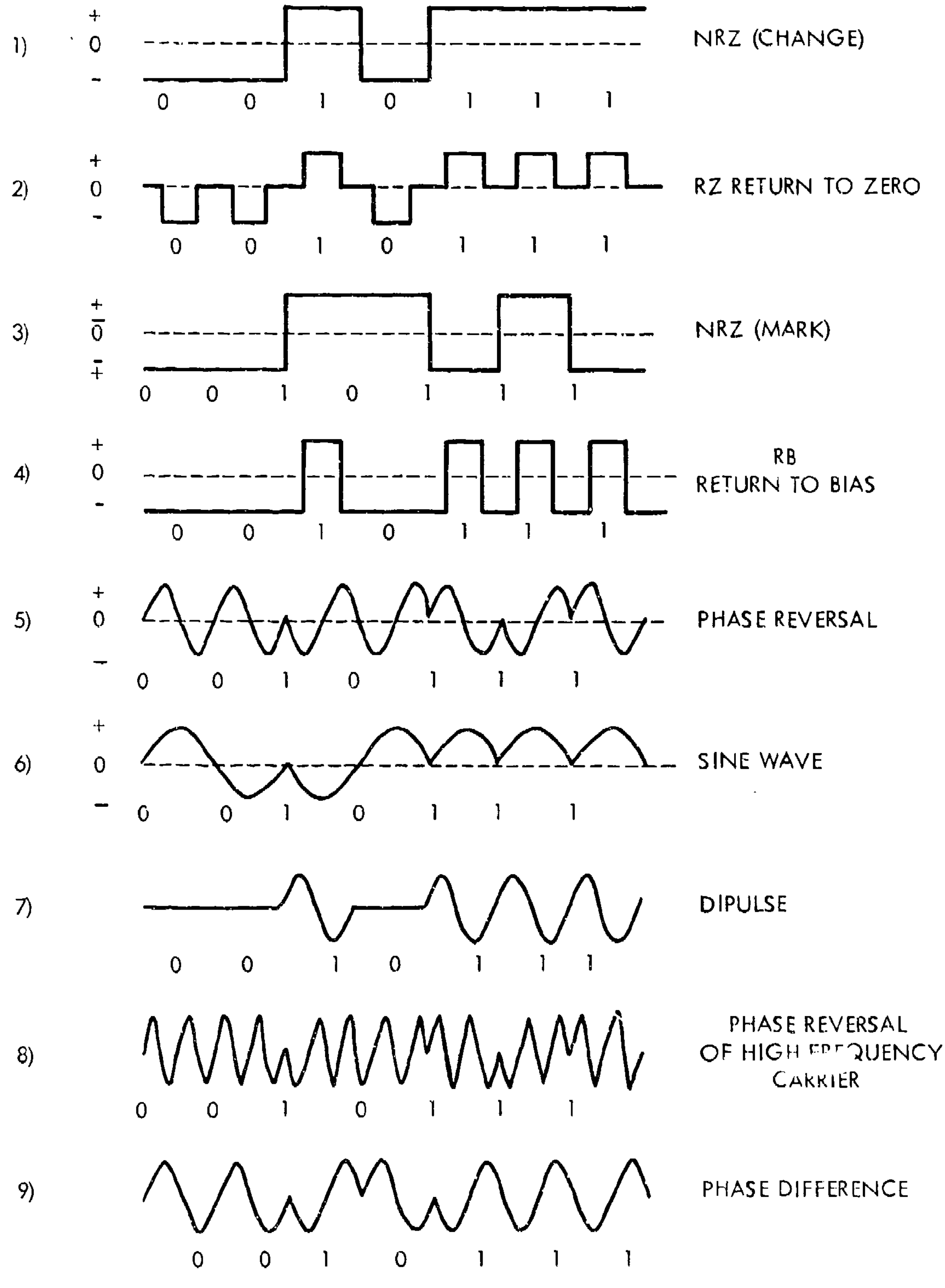


Figure 1-10 Binary Modulation

The arrangement of the code sequence in a binary transmission system is called the format. In general the format is defined by the arrangement of bits in each code group representing a sample value (which is sometimes called a word) and the arrangement of these code groups in respect to one another. The bits within a particular coded word may consist of: information bits which are weighted binarily as previously described to represent the sample value; a parity bit which takes on the polarity necessary to make the total number of one bits per word either even or odd (dependent upon whether even or odd parity is to be used); and synchronization bits which are normally of fixed polarity. Either or both of the latter types of bits might be missing depending upon the requirements of the system. Parity bits serve the purpose of allowing detection of words with a single bit in error. However, parity is of questionable value in a radio transmission link since only in a relatively small area of signal-to-noise ratios is the probability of a single bit error probable enough to be a bother and much more probable than the occurrence of two errors within the word. For this reason parity bits are quite often not included in the transmitted format of radio links. However, in the ground data handling process parity bits are almost always used since the statistics associated with the introduction of errors in the code by the data handling equipment are quite favorable to their detection by parity. The synchronization or timing bits which may appear every word or may appear after a certain small sequence of words are usually called word synchronization bits. Virtually all presently operating binary PCM systems have included some form of word synchronization, although some presently under development do not.

The arrangement of words in respect to one another is quite flexible and varies between almost all systems. In many systems it is possible to include words containing different numbers of information bits. This is particularly the case when one bit words (which are sometimes called bi-level or events data) are to be inter-mixed with words of a larger fixed number of information bits. In the simplest cases the information channels are sampled sequentially with fixed word length (such as was illustrated in Figure 1-3). In this case each word represents the code for a separate information channel, appearing sequentially in time. The sequence is repeated each time the commutator completes a cycle. This entire cycle is normally called a frame. In most recent PCM systems the programming of channels within a frame has been quite complex, with some channels being sampled more often than others. This can be best visualized by considering a commutator with a very

large number of terminals with some of the terminals tied together so that some channels are sampled more often than others.* It is necessary to also supply timing information to designate the start of the frame. This is normally done by transmitting a unique or identifiable code pattern in one or more word positions.

(b) Orthogonal Coding Systems

In recent years considerable study has been devoted to the use of codes other than the ordinary binary code described in Section I, 1-2c. as a means of transmitting information. Perhaps the most interesting category of codes is the orthogonal variety. In the early work on information theory it was recognized that codes could be chosen which allowed an exchange between system sensitivity and system bandwidth. The orthogonal coding technique accomplishes this exchange in a fashion similar to that predicted. Thus, orthogonal systems utilizing relatively large RF spectrum space can be received with less transmitted power than other systems transmitting the same information under equivalent conditions. Although, other techniques, such as high deviation frequency modulation, have been used in the past to exchange bandwidth for sensitivity, they do not perform the exchange as favorably as do the orthogonal systems.

The principle of operation involves the use of only a few of a large number of possible binary codes to represent the quantized signal levels. The set of codes to be used are selected in such a fashion that they are mutually orthogonal; that is the cross correlation between any two different codes selected is zero or negative. The correct code can be identified at the receiving station by cross correlating the input word signals with all of the possible transmitted words and selecting the correlator with the largest output. Since the averaging time in the correlation process is an entire word rather than a single bit time, the noise power as compared to a binary system is reduced.

*The different means producing such a program are sometimes referred to as: super commutation, subcommutation and programmed multiplexing. Subcommutation implies that a single channel which appears periodically is supplied by another commutator so that each revolution of the prime commutator, one of the subcommutator channels appear. Super commutation and programmed multiplexing are similar in that they can present the same format but differ principally in technique of supplying the format.

An eight level orthogonal code along with the equivalent eight level binary code are illustrated in Figures 1-11 and 1-12. As can be seen four binary bits are required to achieve the orthogonal combinations meaning that eight of the binary combinations in the orthogonal code are not used. The code levels are shown as plus and minus E rather than one and zero since the evaluation of the cross correlation function requires the "zero" bit to have equal value of opposite polarity from the "one" bit. As can be seen the average of the product of any two of the orthogonal combinations is zero or negative whereas this is not true of the binary code (the average produce varying from 1/3E to -E). The assignment of levels to the orthogonal code is arbitrary since the receiving station identifies the codes word by word rather than bit by bit.

The total gain in power available from use of an orthogonal system as compared to an ordinary binary system can be shown to be approximately one-half the number of binary bits necessary to achieve the number of quantizing levels. Thus for an orthogonal system with eight quantizing levels (corresponding to a three bit binary system) the power gain is approximately one and a half or 1.8 db. An orthogonal system with 1024 quantizing levels (corresponding to a 10 bit binary system) would realize an approximate power gain of 5 or 7 db.

The number of orthogonal combinations in a word of n binary bi s is 2^n. Thus in order to allow representation of all quantization signals with mutually orthogonal signals, the number of bits per word in an orthogonal system must be equal to one-half the number of quantizing levels. This, then, requires an increase in bandwidth over an equivalent binary system of a factor equal to half the quantization levels divided by the number of binary bits necessary to realize the quantization levels in a binary system. For the system with 8 quantization levels the bandwidth must be increased by 4/3, while the system with 1024 quantization levels the bandwidth must be increased by a factor of 512/10 or 51.2. The slope of power vs. bandwidth becomes small as the bandwidth becomes large.

(c) Other Digital Systems

As previously mentioned, there are an unlimited number of different types of digital systems. Although, binary weighting has been used almost exclusively in systems involving RF link transmission, other two level codes have often been used in data handling equipment. Perhaps the most common of these is binary coded decimal (BCD) which consists of sequences of four bit binary pattern. Each four bit binary pattern is

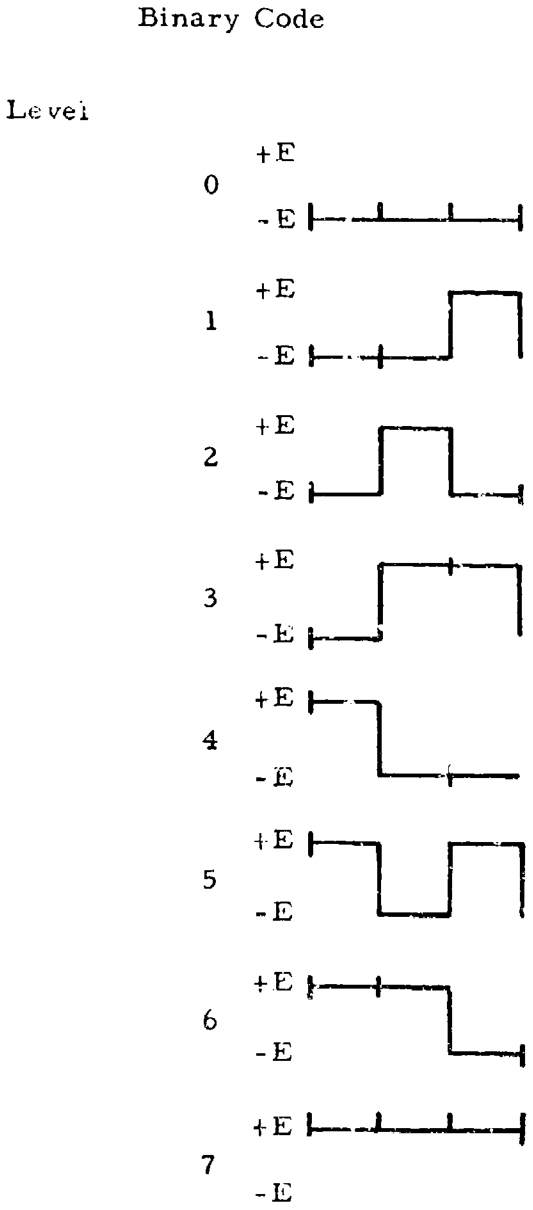


Fig. 1-11 Eight Level Binary Code

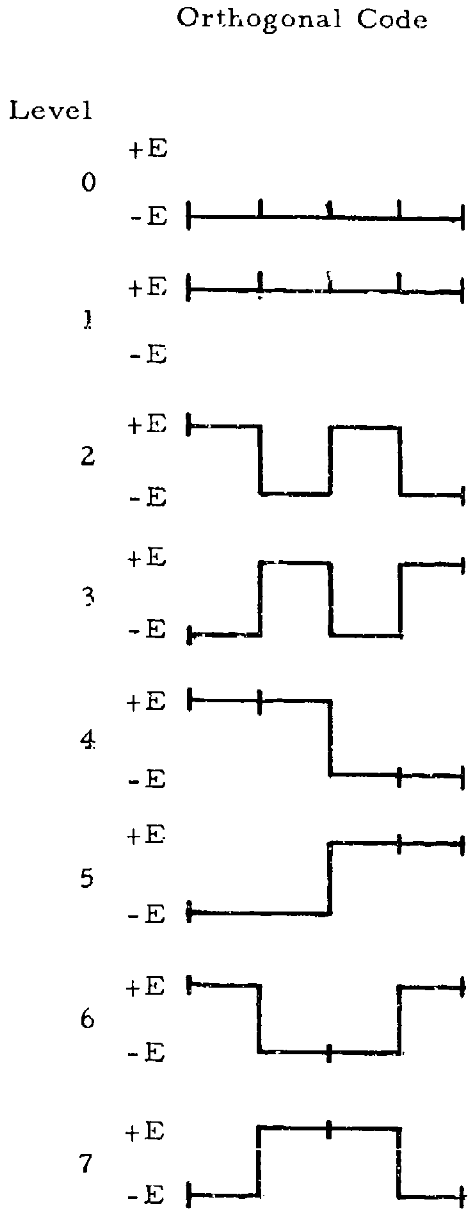


Fig. 1-12 Eight Level Orthogonal Code

used to represent a number from zero to nine. The four bit patterns are than used in decimal form to represent the total number. Thus twelve bi-level bits are necessary to represent a number between zero and nine hundred and ninety-nine, the first four bits representing the decimal values for the hundred column, the second four bits representing the decimal value for the ten column, and the last four bits representing the decimal values for the one column. Since all of the binary combinations are not used, this code is somewhat inefficient from the standpoint of a transmission system (10 binary bits can represent 1024 levels) but is convenient for readout purposes.

Other two level codes such as cyclic or grey code have also been used (see Reference 48). In addition trinary or three level codes have been discussed in literature and at least one instance exists where a four level pulse system was used for telemetry.

Error correction codes have been used which use several bits per word and hence lie between (in complexity) the parity bit, which is an error detecting device, and orthogonal coding schemes which are extreme cases of error correcting codes. Such codes are particularly useful in wire transmission of digital data handling systems where the probability of a single error per word is significant but the probability of more than one insignificant.

(d) Errors in Digital Systems

Probably the tendency toward digital systems which appears in telemetry today is due to the relatively good accuracies which can be achieved. Although a considerable amount of analytical effort has gone into showing the generally advantageous exchange between system bandwidth and system sensitivity* available in digital systems, it is probably the reduction in systematic errors which can be achieved in digital transmission systems that has provided the most universal appeal. The errors in a digital system will be categorized as:

*The emphasis placed on this may be due in part to the relative ease of handling discrete transmission systems with a classical information theory approach. The trade off between sensitivity and bandwidth is best visualized by use of information theory.

1) Analog errors (drifts, bandlimiting, non-linearity, etc. in analog portions of the system)
2) Digital dropouts
3) Quantization errors
4) Interpolation errors
5) RF Link errors

Since most digital systems contain some analog circuitry, (up to the digitizer at the transmission end and after digital-to-analog conversion at the receiver if analog readout is required) errors due to drifts, etc. similar to those previously discussed in connection with analog time-division multiplexed systems can exist. All of these errors are systematic rather than fundamental and in general can be reduced to a much smaller value than can the equivalent errors in an analog system since drifts, distortion and bandlimiting in the transmission link beyond the converter causes no error at all unless they are very severe.

The systematic errors associated with data after it has been digitized are called dropouts. In a binary coded system the principal source of dropouts are in the tape recording process due to tape imperfections.

There are three fundamental errors in a digital system. The first is quantization error. If the signal into the converter takes on a continuous range of voltage and the signal out of the converter can stand for only discrete values there is usually a difference between the input and output which is called quantizing error. The maximum quantizing error is equal to one-half the quantizing range and if the signal is presumed to equally likely to be at any place within the quantizing interval, the rms quantizing error is the quantizing interval divided by the square root of twelve.

Since the digital systems discussed herein are time-division multiplexed systems the problems of interpolation and the errors associated with the process are identical to those of analog time division system. About the only difference involves the relative ease of interpolating with a digital computer which may provide some advantage over other techniques.

The RF link errors in digital systems behave in a different fashion than those of analog systems in that a very sharp threshold exists. When the signal strength is very much above this threshold almost no errors occur due to noise in the RF link. However, if the signal strength

is much below that threshold the data is very noisy. (References: 1-9 and 37 through 53 consider digital systems.)

d. Sub-Multiplexed and Combination Systems

In frequency division transmission systems it has been common to sub-multiplex some of the wider band subcarrier channels. This sub-multiplexing usually involves the use of a time-division multiplexed waveform as the modulation of one of the subcarrier channels as illustrated in Figure 1-13. The use of sub-multiplexed channels of this nature allows the total number of measurements handled by the transmission system to be increased considerably. The frequency content of the sub-multiplexed measurements must be low relative to that which could normally be transmitted over the subcarrier channel.

The most common types of sub-multiplexing have been PAM/FM/FM and PDM/FM/FM although almost all varieties have been used for some applications. Sub-multiplexing by frequency division multiplexing with low frequency channels and using the composite signal to modulate a higher frequency subcarrier has also been used. This is called FM/FM/FM. In many systems different types of sub-multiplexing are used on different subcarrier channels.

Although combined telemetry systems have not been widely used to date, there is some indication that they may receive increased attention in the future. To illustrate what is meant by combined telemetry systems, two examples will be presented.

The first example illustrated in Figure 1-14 combines a general time-division multiplexed system with frequency division subcarriers. Since the time-division waveform can be expected to occupy the lower frequency region of the baseband, higher frequency subcarriers can be added in a linear summer in such a fashion that they are separable by virtue of baseband frequency content.

The second example involves the combination of two time-division systems, as illustrated in Figure 1-15. The modulating waveform is further time multiplexed between the two time-division systems. Such a scheme using PAM and PCM (called PACM) has been considered in literature (Reference 2). Analytical papers on the specific subject of sub-multiplexed and combination systems can be found in references 1 and 2, and 54 through 60.

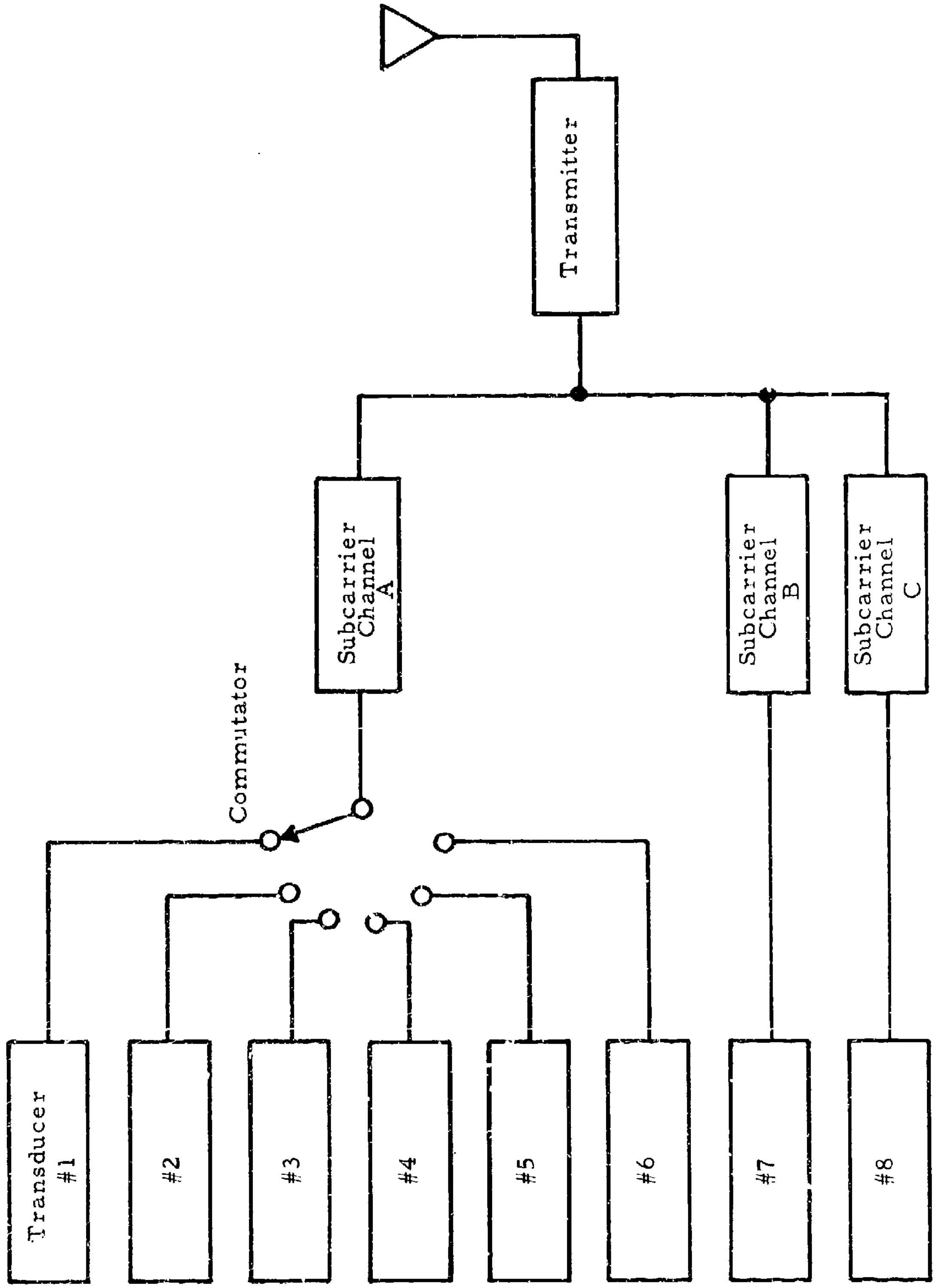


Fig. 1-13 Example of Sequential Sampling System

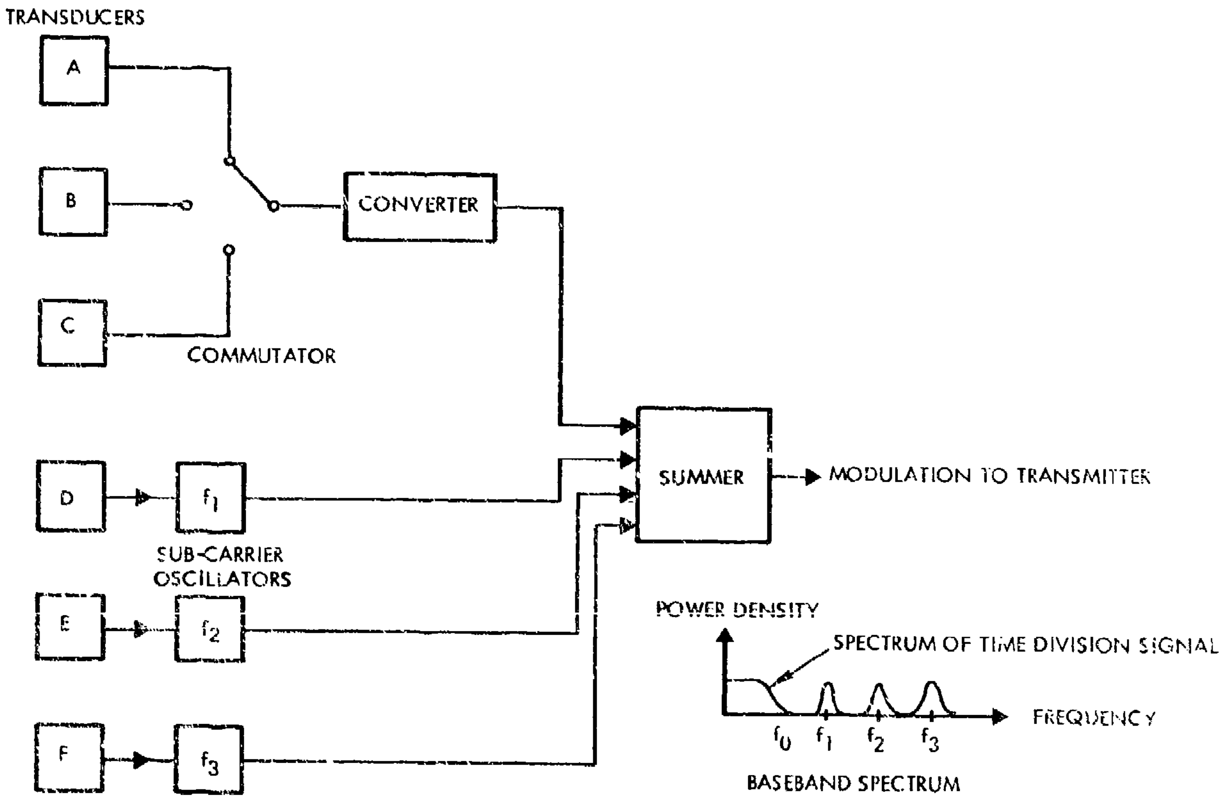


Figure 1-14 Combined System with Frequency Division Multiplexed Baseband

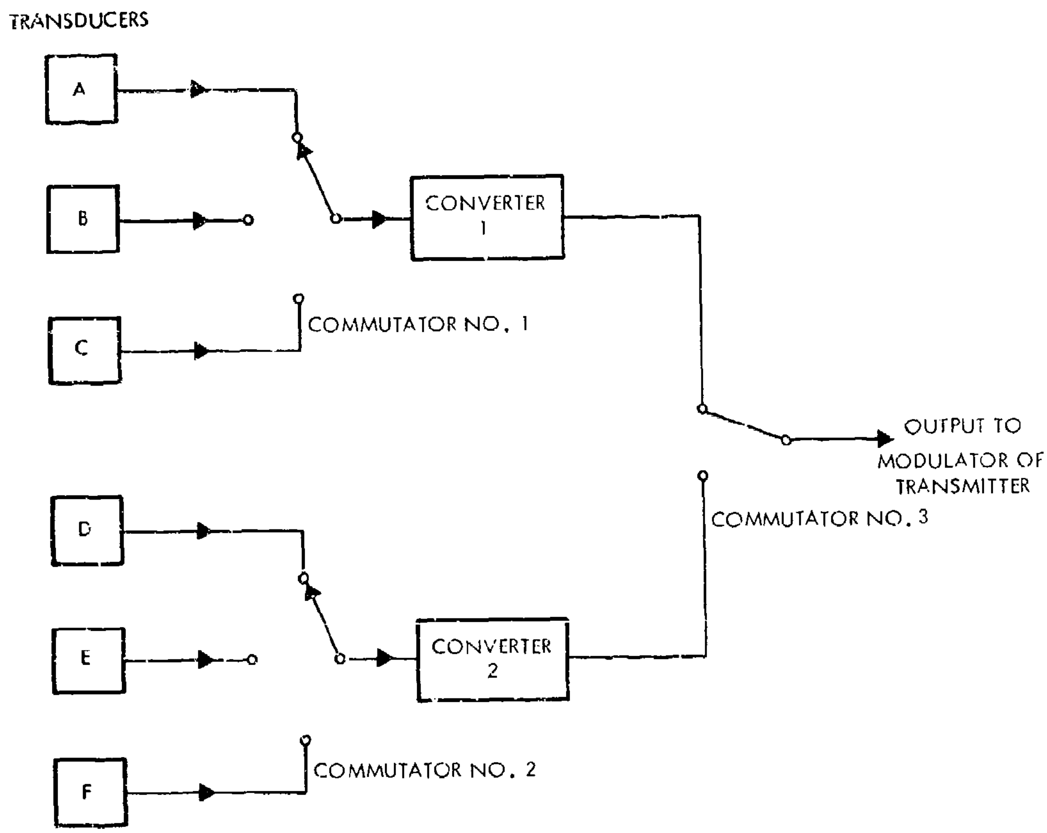


Figure 1-15 Example of Combined System with Time Division Multiplexed Baseband

a. FM/FM

Shortly after World War II the Research Development Board (RDB) established a set of standards for FM/FM telemetry. This set of standards, which formed the foundation for the present day Inter-Range Instrumentation Group (IRIG) Standards, specified the center frequencies of the subcarrier oscillators, and the bandwidths allotted to each subcarrier channel. With these parameters tied down, and the subsequent production of standard subcarrier oscillators and subcarrier discriminators, FM/FM became the most widely used military telemetry system. This ascendency has lasted to the present time, and has carried over into some of the western European nations as well. As time progressed, the number of measurements required of telemetry systems increased. The limitations in maximum number of channels allowed in original and present day standards for FM/FM were alleviated by establishing standards for sub-multiplexing the higher frequency subcarrier channels. Thus standards for PAM/FM/FM and PDM/FM/FM were generated. The complete standards are given in Appendix I. For convenience, the table showing the subcarrier frequency locations and the bandwidths associated with the individual subcarrier channels are given in Table 1-1. As can be seen, the subcarrier channels vary from 400 cps to 70 kc in center frequency with frequency response variations of 6 cps to 1.05 kc.

Due to the variation in information capacity of the subcarrier channels, it is necessary for the user to take care in setting his system up if he is to make the best use of the system. Table 1-2 (Ref. 61) gives an idea of some of the measurements and what measurands can be accommodated by various subcarrier channels.

In addition to selecting the proper subcarrier channel for each measurand, the taper of the system must be adjusted. The taper determines the frequency deviation of the prime carrier caused by each subcarrier and hence determines which channels are most likely to be effected by crosstalk and RF link noise. Discussions as to how to properly adjust the taper are included in Refs. 61 and 62.

Examples of modern day use of FM/FM and subcommutated FM/FM systems may vary from its use for operational evaluation of small missiles (Ref. 63) to design testing of an ICBM, Refs. 64 through 66) to measurements of hydrographic quantities (Ref. 67).

Table 1-1. Maximum Sampling Rates for Manually Separated Data

	Net Sample Lengths* (Milliseconds)		Sampling Rates** (Samples/Second)	
Channel (cps)	Conservative Values	Min. Values	Conservative Values	Max. Values
400	660	165	1.52	6.0
560	500	125	2.00	8.0
730	363	91	2.76	11.0
960	296	74	3.38	13.5
1,300	200	50	5.00	20.0
1,700	160	40	6.25	25.0
2,300	114	28.5	8.75	35.0
3,000	89	22.2	11.2	44.8
3,900	66	16.5	15.0	60.0
5,400	50	12.5	20.0	80.0
7,350	36.4	9.1	27.5	110.0
10,500	25.0	6.25	40.0	160.0
14,500	18.2	4.55	55.0	220.0
22,000	12.1	3.02	82.6	330.0
30,000	8.9	2.22	112.0	448.0
40,000	6.6	1.65	152.0	609.0
52,500	5.1	1.25	196.0	785.0
70,000	3.8	0.95	263.0	1,050.0
Optional Bands (± 15% Deviation)				
22,000	6.0	1.5	165.0	660.0
30,000	4.5	1.12	222.0	888.0
40,000	3.3	0.825	303.0	1,212.0
52,500	2.5	0.625	400.0	1,600.0
70,000	1.9	0.475	526.0	2,100.0

* Net sample is defined as the time a sampling device dwells on a function. This is equal to the gross sample or the period between the start of two adjacent samples only when no time is lost in switching from one sample to the next.

** Assuming no lost time between samples. Multiply these values by the duty cycle for the actual values.

Table 1-2. Subcarrier Bands for Selected Measurands

Subcarrier Frequency (kc)	Intelligence Frequency (cps)	Suggested Measurands
1.3	20	1. Linear or constant acceleration
1.7	25	2. Equipment supply voltages (plate, heater, grids, etc.)
2.3	35	3. Accumulator or pump pressures
3.0	45	4. Slowly varying positions
3.9	60	5. Static or slowly varying forces
		6. Conducted temperature
5.4	80	1. Low frequency vibration
7.35	110	2. AGC voltages
		3. Servo system measurements
10.5	160	1. Pressure surges and shocks
14.5	220	2. Radiated temperature
		3. Loading in piston rods, struts, etc.
22	660	1. Vibration
40	1200	2. Monitoring of actuating voltages
70	2100	3. Rapid motion

A standard FM/FM was described (Ref. 63) for the purpose of operational testing of the Hound Dog missile. Since a relatively small number of different quantities were to be monitored, sub-multiplexing was not required.

In the Atlas Intercontinental Ballistic Missile program, FM/FM and PAM/FM/FM was used both in in-flight testing (Ref. 64) and ground testing and checkout (Ref. 65 and 66). The in-flight systems described contained 16 subcarriers, these being channels 1-13 and channels A, C and E. The upper seven subcarriers were sub-multiplexed with a total of 168 PAM channels, with sampling rates varying from 2.5 samples per second to 30 samples per second.

FM/FM and PAM/FM/FM systems have also been used in connection with the Jupiter, Pershing, and Juno II missile programs (Ref. 68) and the Saturn (Ref. 69). The system described for the Saturn booster is capable of handling 216 channels by using PAM subcommutation on eight subcarrier channels.

FM/FM and PDM/FM/FM systems have been used for aircraft testing (Ref. 73). In the system described, ten FM/FM channels were used with the upper two sub-multiplexed with 245 PDM channels. PDM/FM/FM was also used in connection with the Bomarc interceptor program (Ref. 71).

Although FM/FM has not been used to a large extent in space work, it is used in the Mercury manned orbital program (Ref. 72). Two standard FM/FM links are used with four subcarriers in use on each. Channels 5, 6 and 7 contained respiration and electro-cardiogram information. Channel 12 was sub-multiplexed with ninety PAM channels sampled at 1-1/4 sps. The low frequency channels deviated the prime carrier 3 kc each while the deviation caused by the high frequency channel was 10.5 kc.

Many other descriptions of past and projected uses of FM/FM exists in the literature. Ref. 73 through 81 should provide a sampling of the more recent articles of this nature.

b. FM/PM

The principal use of FM/PM to date has been in connection with the "microlock system" (Ref. 82) which has been used extensively

in our space program. This system consists of a few of the lower frequency standard IRIG subcarrier channels which phase modulate a prime transmitter. The phase modulation index is adjusted to assure the presence of a carrier signal which is required by the phaselocked receiver at the receiving site.

In the first U.S. satellite, Explorer I, launched in early 1958, channels 2, 3, 4 and 5 were used to monitor skin temperature, internal temperature, micrometeorites, and cosmic rays. Exploere III carried a similar system. (Ref. 83). The first U.S. lunar probe, Pioneer I launchedon October 11, 1958, contained an FM/PM system utilizing channels 1-5. The quantities monitored and the subcarrier channels used were (Ref. 84):

1) Search coil magnetometer (Channel 2)
2) Micrometeorite detector - flux and momentum (Channels 4 & 5)
3) Internal temperature (Channel 3)
4) Ionization chamber (Channel 1)
5) Facsimile TV scan

The facsimile was to be carried on a separate link but failed to function properly.

Similar telemetry systems were carried on Explorers IV and VI and Pioneers II, III and IV (Ref. 85). Explorer VI also carried a digital link as did Pioneer V which will be discussed later.

In some instances in the past phase modulation prime transmitters have been used in standard missile FM/FM systems. However, the receivers have contained frequency rather than phase demodulators and the transmitted signals have received pre-emphasis so that the link has been FM/FM rather than FM/PM.

The microlock system achieved excellent sensitivity and was undoubtedly a major contributor to the success of the early United States space efforts when transmitted power was at a premium. More recently, however, the larger information capacities required in space and satellite missions and the rising popularity of digital transmission systems have decreased the applications of FM/PM.

c. FM/AM

Although FM/AM has not been extensively used, there has been at least one system in continuous use. This is the telemetry system developed by NACA (now NASA) and employed at Langley Field--Wallops Island Facilities of NASA.

The FM/AM technique is basically the same as FM/FM (both are frequency division systems) with the exception that the output of the FM/AM subcarrier oscillators modulate the amplitude instead of the frequency of the transmitter. At the receiving terminal, the input data is recovered by channel filters and discriminated to obtain the analog quantity. The NASA channel and frequency allotments are shown in Table 1-3. The block diagram of the ground system is shown in Figure 1-16. In this system, the tape recorder is used to store data for later processing.

Recently, efforts have been made to develop FM/AM as a replacement for FM/FM (Ref. 10) with the argument that the hardware limitations which precipitated the original decisions to standardize on FM/FM are no longer valid. Another FM/AM system is described in Ref. 86.

d. Other Frequency Division Systems

As has previously been mentioned almost all combinations of prime and subcarrier modulation techniques have been either used or suggested. Some of these are: AM/FM (Ref. 87) proposed for physiological measurements; SS/FM (Ref. 88) for vibration channels in missile testing; PAM/FM/AM and special purpose FM/FM (Ref. 89) in the Tiros weather satellite; FM/SS (Ref. 90); and PDM/FM/AM and AM/AM (Ref. 85) in connection with the Vanguard program.

e. Analog Time-Division Systems

The majority of the uses of PDM and PAM have been in connection with sub-multiplexed FM/FM systems which have been previously discussed. However, a PDM/FM system for aircraft testing has been described (Ref. 70) which could handle up to 88 active channels at a sampling rate of 16 2/3 sps. Other systems involving the use PDM or PWM used to modulate a prime carrier directly are described in Ref. 91 through 94.

Table 1-3. NASA FM/AM Channel and Frequency Allotments

Channel	Filter Frequency (kc)	Filter Passband
1	72.5±2.5	70.0 - 75.0
2	82.5	80.0 - 85.0
3	97.5	95.0 - 100.0
4	110.0	107.5 - 112.5
5	119.5	117.0 - 122.0
6	129.5	127.0 - 132.0
7	139.5	137.0 - 142.0
8	150.0	147.5 - 152.5
9	160.5	158.0 - 163.0
10	170.0	167.5 - 172.5
11	179.5	177.0 - 182.0
12	190.5	188.0 - 193.0
13	199.5	197.0 - 202.0
14	217.0±5.0	212.0 - 222.0
15	222.0±10.0	212.0 - 232.0
16	238.0±5.0	233.0 - 243.0

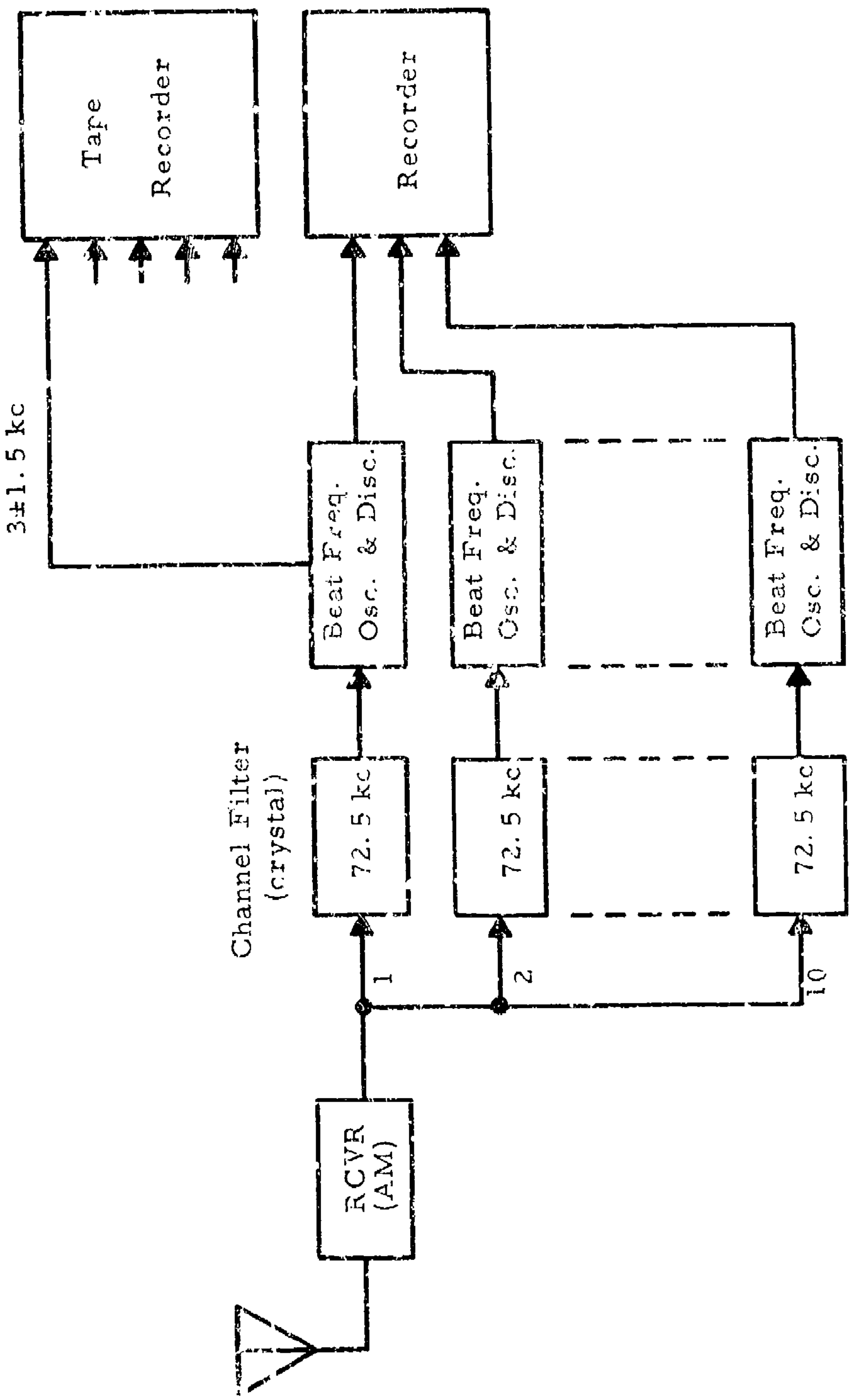


Fig. 1-16 NASA FM/AM Ground System

A thirteen channel PAM/FM system missile application has been described in Ref. 95. The system is capable of sampling at rates as high as 50 kc and uses 50% duty cycle.

A PPM system was employed by Naval Research Laboratories with operational characteristics as shown in Table 1-4. Other applications of PPM/AM include the Vanguard missile program (Ref. 96), and physiological telemetry systems (Ref. 97). General purpose systems are described in Ref. 98 and 99.

f. Pulse Code Modulation System

The growing quantities of telemetry data and the advent of digital computing devices dictated some time ago the use of digital ground data handling systems. Although, binary pulse code modulation had been considered for voice transmission purposes in the late forties (Ref. 100), its use in airborne telemetry transmission systems began in the middle fifties with the development of the AKT-14, UKR-7 system for Wright Air Development Center (Ref. 101 through 106). From this time on the growth in the number of digital transmission systems in telemetry applications has been rapid. A survey of the PCM systems for telemetry purposes was conducted by R. L. Sink (Ref. 107) in 1960 and is shown in Tables 1-5, 1-6 and 1-7. Since the time of compilation of the table most of the systems pending service or in-development have been put to active use. For instance, the PCM system for A. C. Spark Plug Division of General Motors has been used successfully in seven flights of the Titan ICBM thus far. In addition many of the large booster programs in the future appear to be planning upon the use of PCM telemetry systems and in this area it seems likely that PCM may supplant FM/FM as the most commonly used type of telemetry system.

A second area in which digital systems appear to be gaining supremacy is in space telemetry. The signal-to-noise advantages coupled with the relative reliability and flexibility of digital circuits compared to analog circuits has made the use of digital systems appear quite attractive in applications where long periods of unattended operation are required. The Telebit system described in Table 1-5 has been successfully used in both Explorers VI and VII and Pioneer V (Ref. 108, 109 and 110). A feeling for the growing capability of digital space telemetry system can be obtained by considering the PCM system being designed for NASA for the Nimbus weather satellite which will multiplex and code 924 different channels using less than 2 watts of power.

Reference material describing other PCM applications may be found in Ref. 111 through 119.

Table 1-4. NRL Telemetry Transmitting Set AN/DKT-7(XN-2)

Channels	15
Sampling Rate	312.5 samples per second
Supercommutation	4 channels may be cross-strapped for 1250 sps
RF Frequency Link	220-239 mc
Transmitter Power Out	40 watts (peak pulse power)
Accuracy:	±2% (±1% with external calibration)
Power Input	28 v dc at 3.5 amps 6.7 v dc at 11.3 amps
Commutation	Electronic
Signal Input	0-5 volts
Pulse Interval	200 usec
Bandwidth	100 kc approx.

Table 1-5. Programs of PCM Telemetry Equipment

	ACTIVE USE					PENDING SERVICE(3)					OUT OF SERVICE			IN-DEVELOPMENT		
EQUIPMENT OWNER	Space Tech. Labs.	Holloman ADC	Douglas Aircraft (Santa Monica)	North American Aviation (Columbus)	Jet Propulsion Lab. Sperry (Utah)	Northwestern Univ.-Aerial Measurements Lab. (BuAer-Sponsor)	Republic Aviation N.A.T.C. Patuxent	Northrop (Hawthorne)	General Electric (Edwards)	Eglin AFB	WADC	North American Aviation (Los Angeles)	Martin Co. (Baltimore)	Boeing (Seattle)	A. C. Spark Plug (Milwaukee)	Jet Propulsion Lab. Sponsor
DESIGNATION	Tele-bit	Mark II	ADMS	Mars	(Sergeant Missile)		SPGM-8&6-15, 16		Project Advance		AN/AKT-14(4)	Daisy II	YPGM-1 System	(Minuteman Program)	(Titan Program)	Digilock
MANUFACTURER	Space Tech. Labs.	Radiation	Datalab Division of CEC	N.A.A. Columbus	G-E Electronics - Gelton Ind.	Datalab Division of CEC and Northwestern Univ.	Epsco	Radiation	Radiation	Epsco	Radiation(5)	N.A.A.	Martin (System Eng.) and three sub-contractors	N.A.A.-Autonetics and Radiation	Radiat	Epsco Electronics
NO. OF SYSTEMS	6	1	4	2	Approx. 30	1	3	1	3	1	No information	1	1	None delivered	None delivered	1 ordered. None delivered
NO. IN(1) ACTIVE USE	1(2)	1	2	1	Approx. 30	0	0	0	0	No information	No information	0	1(6)	0	0	0
NO. HRS. USED PER MO. TO GATHER DATA	720(2)	4	25 to 30	5	1 (Per System)	0	0	0	0	No information	No information	50 Flights 1957-1958	10	0	0	0

NOTES: (1) Active use is defined to include only those equipments that are being used in a data gathering situation where the primary effort is not to prove operation of the PCM system. Spare systems or components are not listed as active.

(2) One successful flight in Explorer VII. Telemeter went silent in approximately 1500 hours.

(3) Additional programs are believed to exist but information was either obscure or could not be obtained.

(4) AN/AKT-14 Systems have also been delivered to Convair-Astronautics, and Emerson Electric.

(5) Radiation, Inc., did not have antenna transmission or reception responsibility on AKT-14.

(6) Installed in flight test aircraft from January through July 1959, during which time system de-bugged and used to acquire data to complete test program. Termination of Seamaster contract interrupted further use of system.

Table 1-6. Operating Parameters of PCM Systems

EQUIPMENT OWNER	Space Tech. Labs.	Holloman ADC	Douglas Aircraft (Santa Monica)	North American Aviation (Columbus)	Northwestern Univ. (Aerial Measurements Lab.)	Jet Propulsion Lab. Sperry (Utah)	Republic Aviation N.A.T.C. Patuxent	General Electric (Edwards)	Eglin AFB	Boeing (Seattle)	A. C. Spark Plug (Milwaukee)	Jet Propulsion Lab. Sponsor	Martin Co. (Baltimore)
WORD STRUCTURE (No. of Bits)	12 Max. 10 Digital or 6 Analog + 4 Other	15	10 + Sign for Data 1 Parity 1 Event	9 + Sign	9 + Sign for Data 1 Parity, 3 Random Events	12 Data (3CD) 4 Parity 6 Word Ident. 8 Other	9 + Sign 3 Event 1 Parity 13 Digital	11 for Data 1 Parity	9 + Sign 3 Event 13 Digital	8 Data mixed with Computer Data Total of 27	27 of 8 Analog, 8 Digital, 8 Analog + 3 Word Sync	15 Total 5 Data + 11 Redundant	11 Data 1 Parity 1 Word Sync 1 Timing and Frame Sync
FRAME LENGTH (Words)	11	32	20 to 110	180	20 to 50 + "Inserted" Words at Event Periods	12	10 Analog + 15 Digital	90 Analog + 10 of Special Marking	25 Analog + 2 Digital + 2 Time	30 Millisecond Intervals		30	1000
SYSTEM SPEED (In Bits per Sec.)	1, 8, or 64 at 6 Samples/Sec. Max.	264,000 at 24,000 Samples/Sec.	455,000 Max. at 35,000 Samples/Sec.	100,000 10,000 Samples/Sec.	385,000 Max. 1,280 to 32,000 Samples/Sec.	3,360 120 Samples/Sec.	350,000 Max. 25,000 Samples/Sec.	280,000 Max. 20,000 to 2,500 Samples/Sec.	325,000 25,000 Samples/Sec.	345,600 25,600 Samples/Sec. Analog Data, 12,800 Samples/Sec. Digital Data	172,800 ± 10%	409,600 25,600 Samples/Sec. Max.	14,000
SIGNAL SOURCES (No. of Channels and Signal Levels)	16 (Subcom) 0-3V F.S. 3 (Prime) 0-3V F.S. 6 Digital Inputs	32 at 10.23V F.S. or 7 MV F.S. at Amplifier or 32 Digital Inputs	100 Prime ± 10 MV F.S. Each Prime Channel may be Sub-com to 10 or 100 Channels ± 10MV F.S. Total max. capacity 10,000 Channels. 20 11-Bit Digital Inputs	180 at ± 25 MV F.S.	50 at ± 5V F.S. and up to 16 10-Bit Digital Inputs. Special Events may expand frame size	12 at ± 5V F.S.	32 at 5V 13 at 5MV 25 at 5V 20 at 25MV 15 13-Bit Digital Inputs	± 5V F.S. or ± 10MV F.S. In Groups of 15	5 ±50 MV 25 ± 500V	328 Max. at 5V F.S., or 164 at 20MV F.S., or combination of High and Low Level	64 at 5.10 Volts F.S. + 5 8-Bit Digital Inputs + Computer Input	30 Analog 0-5V F.S. 10-Bit Digital Inputs	400 at ± 1V F.S. 600 at ± 30MV F.S. (Any combination totaling 1000 Channels permissible)
RESOLUTION	1/64	1/1023	1/2045	1/1023	1/1023	1/1000	1/1023	1/2016	1/1023	1/256	1/256	1/32	1/1000
ACCURACY	2%	0.4%	1 Bit at 5V 0.2% at 10 MV	1%	± 1 Bit	0.2%	± 0.1% for 5V; ± 1.0% for 25MV	± 0.2% of F.S.	± 0.2%	Not known	1%	3%	0.3% for 1 V 1.0% for 30MV
SYNCHRONIZING A. Frame	Unique Code All "0"	AM Modulation superimposed on FM Modulation	Unique Word All "1's"	Separate Track on Tape	Unique Word All "1's"	None. (Each word has distinct identification)	Unique Word	Unique Word All "1's"	Unique Word All "1's"	3-Bit Combined Word and Frame	Classified	Unique Word	Separate Track on Tape
B. Word	0-1 Transition Between Words	Uses Frame Sync	0-1 Transition Between Words	Recorded Only	Recorded Only	(1)	0-1 Transition Between Words	Recorded Only	0-1 Transition Between Words		3 Bits	Must have prior system synchronization during preparatory transmission but can maintain sync with fading	Recorded Only

(1) Each word is a 4 by 7 bit serial parallel combination. Six bits of the first 7-bit "character" of each word is used to identify the word.

Table 1-7. Telemetry Transmission of PCM (existing systems)

EQUIPMENT OWNER	Space Tech. Laboratories	Douglas Aircraft (Santa Monica)	Holloman ADC	N.A.T.C. Patuxent	Jet Propulsion Laboratory Sperry, Utah
TRANSMISSION FREQUENCY SPECTRUM USAGE POWER TRANS. ANT. GAIN BIT RATE	 378 MC 5 Watts 0 DB 1, 3, or 64/Sec.	 1450 MC 3 X Bit Rate 40 Watts 0 DB Up to 525,000/Sec.	 800 MC 2 MC 10 Watts [illegible] DB 264,000/Sec.	 1435 - 1535 MC 2 MC 20 Watts 4 DB 512,000 Max./Sec.	(2) 258.5 MC - 2 Watts 3 DB (3)
MODULATION	PCM-FM-PM (Bi-Phase Sub-Carrier)	PCM-FM	PCM-FM + AM Sync.	PCM-FM	PCM-FM-FM
RECEIVER ANT. GAIN I.F. BANDWIDTH NOISE FIGURE	(1)	 27 DB 2 MC 8 DB	 10 DB 3 MC 6 DB	 10 DB 5 MC 8 DB	 8 DB 0.3 MC 100 DBM
SYSTEM DESIGN LOSS		162 DB			
DESIGN DROP-OUT RATE	1 X 10^{-2}	1 X 10^{-6}	1 X 10^{-5}	Not specified	1 X 10^{-4}
EXPERIENCE DESIGN RANGE ACTUAL RANGE FADE EXPERIENCE	 500,000 Miles at 64 Bits/Sec. Not reported	 100 Miles at 5000 ft. Alt. 125 Miles at 6000 ft. Alt. Altitude-sensitive. Some evidence of multi-path fading due to reflection from near-by buildings.	 3.5 Miles at Gnd. Level 3.5 Miles Problems from multi-path fading from metal post at track, rails of track. Primary transmission problem attributed to AM sync pulse method.	None to date	 Not stated 80 Miles Data not extensive enough to draw positive conclusion.

(1) Various receiving sites at Hawaii, Cape Canaveral, Manchester, etc.

(2) Parallel output to seven FM sub-carrier oscillators.

(3) RF link multiplexed with other information besides PCM.

g. Orthogonal Systems

An orthogonal system utilizing 32 quantization levels has been developed and is popularly known as Digilock. The Digilock system will accept either analog or digital input signals to the airborne equipment. Analog inputs are commutated, converted to digital form in the analog to digital converter, and passed to the Digilock encoder. Digital data is programmed directly to the encoder. The encoder unit quantizes the input data into binary code sequences which are used to modulate the transmitter, each value of data being represented by a different code sequence. In the ground station, the received signal is demodulated and applied to the input of a matrix of matched filters. Each filter "matches" one of the many possible code sequences. A decision device, the output selector, compares the outputs of all filters and selects that filter having the maximum output. The data value corresponding to this matched filter is then recorded and used for external system functions in either digital or analog form. Alternatively, the output of the receiver may be recorded at any remote location and later processed at a central decoding station.

Specifications and performance of the Digilock system are given in Tables 1-8, 1-9, and 1-10.

h. PACM/FM

Beginning in February, 1957, a telemetry system study program was undertaken by Aeronutronic under Contract Number DA-36-039 SC-73182. Prime objectives of the study were: (1) to forecast future telemetry test loads at the test ranges and to predict the user's requirements of an individual telemetry system in types and amount of information to be transmitted over the next decade; (2) to recommend suitable operating frequencies for future telemetry systems; (3) to examine the various forms of modulation and data multiplexing, and recommend optimum techniques for future systems; (4) to investigate the performance of present telemetry systems and to recommend improvements.

The requirements in terms of data parameters were based upon the telemetry user's needs as determined from the results of the user requirements survey. The survey covered factors such as data accuracies, information bandwidth, number of sensors, and total data rate. It was determined that an "average" requirement is one in which 75 sensors are required, the average data accuracy is 2.5% of signal range, and the total data rate is equivalent to 75,000 bits per second. The single point most evident from the user requirements survey is that a general purpose system intended to accommodate a majority of user needs must be a very flexible

Table 1-8. Digilock Specifications

Inputs:	100 binary inputs per frame from either analog or digital sources, commutated by the Digilock encoder.
Data Rate:	One complete commutation frame per second.
Output Signal:	Binary sequence suitable for phase modulation or of commercial frequency modulation.
Active Elements:	Silicon transistors throughout.
Power Requirements:	7.5 v at 160 ma (1.2w)
Weight:	2.25 lbs.
Size	8" x 1.25" x 6"

Table 1-9. Digilock Tested Environmental Capability

Temperature	-20 to +70°C
Acceleration:	60 g
Vibration:	20 g from 100 to 2,000 cps

Table 1-10. Tested Application of a Digilock System

Carrier Frequency:	240 mc
Transmitted Power:	200 mw
Transmitting Antenna Gain:	0 db
Receiving Antenna Gain:	27 db
Receiver Noise Figure:	4.5 db
Communication Range:	50,000 miles

system indeed. The requested accuracies range from 0.1% to 20% with most requirements having different accuracy requests among the data channels. Some of the large missile and aircraft tests utilize over 400 sensors, and while the average data rate was 75,000 bits per second, nearly 10% of the requests were for more than 1,000,000 bits per second. It was seen that a single general purpose system would have to provide data rates of 100,000, 200,000, and 400,000 bits per second, at least.

Anticipation of increased data requirements and further congestion in the telemetry bands also required that efficient use of the RF spectrum be a major factor in the choice of a general purpose system. The efficiency of a system in spectral utilization is a function of its interference susceptibility and interference generation.

In addition to consideration of flexibility and spectrum utilization, considerations of a more general nature which were taken into account in the design of the conceptual system were as follows:

1. To the greatest extent possible, the system should be compatible with existing input and output devices, i.e., transducers, data display, recorders, computers, etc.

2. The wide application of telemetry at the test facilities and ranges represents a very large investment in equipment and effort, consequently the maximum utilization of these is desirable.

3. The greatly increased cost of vehicles and their non-recoverable nature demands increased emphasis on reliability as a design consideration.

4. Size and weight of the vehicle-borne components is important in view of the desired usefulness in applications ranging from small research vehicles to ICBM's.

Some of the considerations noted above represent conflicting demands on the conceptual system design. However, requirements (1) and (2) and aspects of requirement (3) are largely met upon selection of a system which will expeditiously meet most user needs and which the capability of expanding to accommodate the increasing requirements of the future.

The conclusions reached in the course of the study are listed in detail in the Final Report (Ref. 5). The system recommended as a general purpose telemetry system is a combination of PAM/FM and PCM/FM which is designated as PACM/FM. The format consists of pulse amplitude channels time-division multiplexed with PCM/FM channels. The time allocated to each pulse amplitude channel is chosen as an integral number of bit times to simplify the timing system. The system is in the evaluation state at present.

SECTION II

TRANSDUCER FUNDAMENTALS

2-1 INTRODUCTION

a. General

This section covers the fundamentals of various physical measurements in an effort to illustrate and provide basic information about transducing devices used to translate the measurements to usable signals as employed in telemetering systems. In many cases it is difficult to classify a measurement fundamental as applicable to an existing transducer element or device. However, as new materials, methods and instruments are developed to satisfy new and advanced program requirements, some fundamental relationships will become more useful. For example, the advancements in the use of optical scanning techniques (color TV included) has made more useful, many measurement fundamentals based on visual indications, rather than mechanical or electrical signals.

It would, of course, take several text books to adequately discuss each of the major types of measurements involved. References have been given pertaining to historical development, detailed derivations, and evaluation reports to supplement the limited descriptions that follow. The reader may also question the inclusion of certain types of transducers. Synchros, for example, are not generally thought of as "telemetry transducers." However, telemetry engineers must be familiar with synchros, resolvers, control transformers and other like equipment, since they are often called upon to handle signals (shaft position, ac voltage, etc.) from servo and computer systems. The question as to what equipment should be included in this handbook leads to the next question of what is meant by "transducer." A brief and explicit definition cannot be easily derived. The Inter-Range Instrumentation Group has adopted the following definition for an instrumentation transducer (See Appendix II): "A device which responds to a phenomenon and produces a signal which is a function of one or more characteristics of the phenomenon." This general definition encompasses two groups of elements as stated by Lion (Ref.120); namely, input transducers and modifiers. As classified by Lion, an input transducer is capable of converting a nonelectrical quantity into an electric signal and a modifier element converts an electric signal into another modified

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120 Lion, Kurt S., Instrumentation in Scientific Research (Electrical Input Transducers), New York: McGraw-Hill Book Co., Inc., 1959, pp. 1-2

electric signal. Lion has defined a third group of elements in the field of electrical instrumentation. These are output transducers, used to convert an electrical signal into a nonelectrical quantity (e.g., meter, strobotron tube). The devices described in this and other sections of the Handbook, and called transducers herein, could be logically separated into these three groups, or their combinations. It may be noted that transducers described in this handbook are, for the most part, input transducers; e.g., pres re, acceleration, and temperature transducers. The telemetry engineer is also concerned with modifier elements such as the conversion of ac power to a proportional dc signal. An example of this is the Hall Watt transducer described in this section. The use of output transducers within telemetry systems is limited to special situations wherein an intermediate element is required between the nonelectrical quantity which is to be telemetered and the input transducers. A case may be the use of a synchro transmitter (input transducer) and receiver (output transducer) wherein the transmitter converts shaft rotation to an electrical signal for remote operation of the receiver. The output of the receiving synchro is a corresponding shaft rotation which, in order to be telemetered, must be mechanically coupled to another input transducer (e.g., potentiometer, differential transformer).

From the preceding discussion, it may be recognized that to advance a definitive statement of the meaning of "transducer" could easily impose limitations on the handbook's coverage and consequently its usefulness to the telemetry engineer. In the opinion of the authors, the handbook should incorporate all significant devices with which the telemetry engineer must work.

b. Transducer Nomenclature

Standard nomenclatures for transducers have not yet been settled upon and adopted by manufacturers and users. However, both groups have recognized their need and organized work is being carried out toward this end. A recent questionnaire prepared by the Instrument Society of America contains a tentative listing which may be used in selecting transducer titles (Ref.121). This listing is shown in Table 2-1 and the following

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121 "Preliminary Questionnaire on Transducers Having Electrical Output," Survey Committee on Transducers for Aero-Space Testing (SCOTFAST), (Committee No. 8A-RP37 of Aero-Space Standards Division of the Instrument Society of America), undated.

Table 2-1. Tentative Nomenclature for Aero-Space Transducers

MAIN NOUN	FIRST MODIFIER (Measured)	SECOND MODIFIER (Restricts Measured)	THIRD MODIFIER (Transduction Principle)		RANGE	UNITS
Transducer	Acceleration Angle of Attack Attitude Displacement Flame Impingement Flow Force Light Intensity Liquid Level Pressure Radiant Heat Flux Speed Sound Level Strain Temperature Velocity Vibration	Absolute Angular Differential Dual Fluid Gage Linear Mass Surface Triaxial Volumetric	Electric Element Type Float Type Force Balance Type Gyro Type Turbine Type Ultrasonic Type Vibrating Element Type Bonded Strain Gage Type Capacitance Type Electromagnetic Self-Generating Type Inductance Type Ionization Type Differential Transformer Type	Magnetostrictive Photo-Electric Type Piezoelectric Type, Amplifying Piezoelectric Type Potentiometer Type Reluctance Type Resistance Type Thermocouple Type Thermopile Type Thermistor Type Unbonded Strain Gage Type Variable Frequency Type	(As applicable)	g r/sec °F gpm lb/min in. deg. in/sec rpm (etc.)

are examples of transducer nomenclatures:

Transducer - Acceleration, Linear, Unbonded Strain Gage Type, ±3 g

Transducer - Pressure, Elastic Element, Potentiometer Type, 0-1000 psig

The nomenclature of a particular transducer does not necessitate the use of all modifiers shown in Table 2-1. The second modifier may or may not be employed and a fourth modifier could be used to indicate further restrictive or special characteristics. Examples of a possible fourth modifier are: Integrating; Logarithmic; Digital, Discrete Increment; Bi-Directional; AC or DC Output.

c. Physical Effects and Transduction Principles

Appendix III provides brief explanations of numerous physical effects and principles, many of which are utilized in transducer designs. Some of the effects have not yet been applied in transducer design, but it is conceivable that research may prove them to be of value under special conditions.

2-2 MEASUREMENT OF DISPLACEMENT AND POSITION

The more frequently used transducers are acted upon by the measurand (a generic term designating any physical quantity which can be measured, detected, sensed, or controlled) to cause rectilinear or angular displacement of one of its integral parts. The magnitude of displacement corresponding to the maximum permissible measurand value may be minute or large. For instance, displacement of the moving mass of a force-balanced (servo-balanced) accelerometer is hardly discernible, yet a displacement must exist in order to obtain a signal proportional to acceleration. Relatively large displacements are encountered in pressure elements such as the bellows and Bourdon tube. Very large displacements occur in transducers which are used for measuring position (e. g., rectilinear potentiometers, differential transformers, inductive potentiometers). The conversion of displacement to electrical signals may be accomplished by utilizing such effects as the change in electrical capacitance between two metal plates due to change in distance between the plates; the change in electrical resistance produced by a movable contact, as in the potentiometer or rheostat; the change in self-inductance

or mutual inductance produced by a movable magnetic element; the voltage produced by force applied to a piezoelectric crystal; and the variation in wire resistance due to mechanical strain.

a. Differential Transformers

(1) Operating Principles

Differential transformers are electromechanical devices for translating the displacement of a magnetic armature in an ac voltage which is a linear function of the displacement. Although their physical configurations vary between manufacturers, they are basically composed of primary and secondary coils wound on a ferromagnetic or air core and a movable armature is used to control the electrical coupling between them. When two primary windings are used, they are connected series aiding. The secondary windings are connected series bucking so that the transducer output is the vector difference in the two voltages induced in the secondaries.

One type of differential transformer configuration and its wiring schematic is shown in Figure 2-1. The ac output versus armature position is depicted in Figure 2-2 (Ref. 122). A dc signal suitable for telemetry purposes may be obtained by use of a demodulator and low pass filter. Basic circuitry for ac to dc conversion is shown in Figure 2-3. In transducer applications, the ac input power is often obtained from a transistorized inverter to allow operation from a dc bus. The inverter, differential transformer, demodulator, and filter are usually contained in one package, along with the sensing element (e. g., bellows). Figure 2-4 is a schematic of a typical inverter,

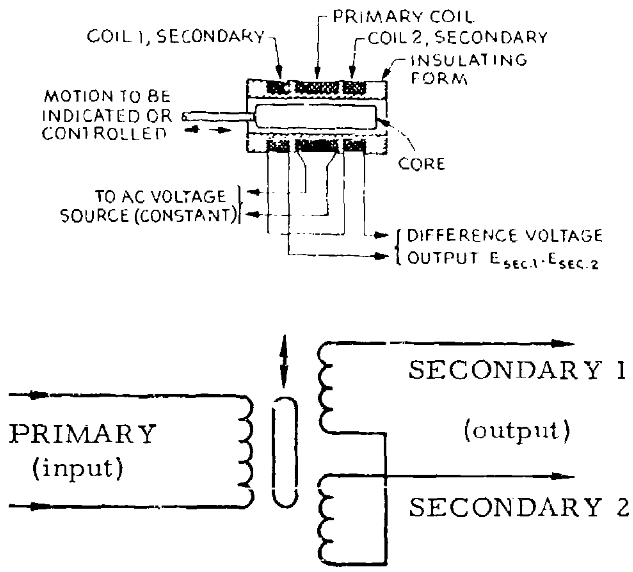

Fig. 2-1. Configuration and Schematic

122 "Notes on Linear Variable Differential Transformers," Bulletin AA-1A, Schaevitz Engineering, pp. 1-2.

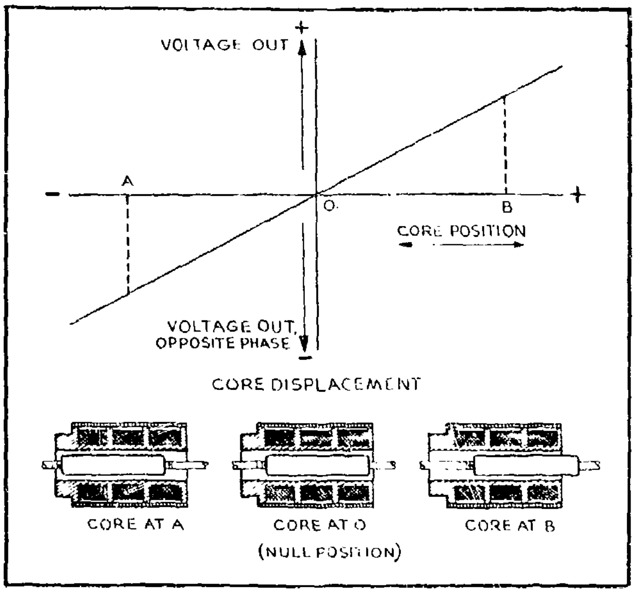

Fig. 2-2. Output Voltage and Phase as Function of Core Position

transformer, and phase sensitive demodulator circuit. The inverter (often called a modulator by manufacturers) generates a square wave carrier which permits simple capacitor filtering to achieve low ripple output. Electro-mechanical response is determined by the degree of filtering required and may be related to ripple approximately as follows:

$$\% \text{ Ripple (rms)} = \frac{10 \times \text{desired response}}{\text{carrier frequency}} \qquad (2\text{-}1)$$

Another configuration of an air core differential transformer with a ferromagnetic armature is shown in Figure 2-5 wherein four windings are wound with different physical relationships (Ref. 123).

The flux distribution of an iron core type differential transformer, designated as the Metrisite by the manufacturer, is shown in Figure 2-6, and one armature design (a conducting loop) is

123 "Handbook of Linear Transducers," Handbook No. R-50, Automatic Timing and Controls, Incorporated, p. 4.

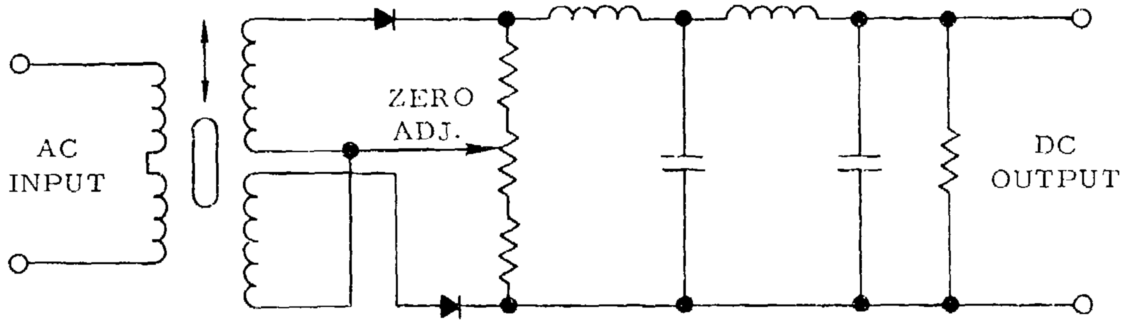

Fig. 2-3. Differential Transformer, Demodulator and Filter Circuits

depicted in Figure 2-7 (Ref. 124). It consists of three coils disposed on three legs of a laminated magnetic structure. In the central leg, there is an air gap, and in this a single-turn loop of conducting material is free to move. When alternating voltage is applied to the central coil, an alternating magnetic flux flows through the central leg, across the air gap, and through the outer legs. The coils on these outer legs are identical and are connected in series opposition. If the conducting loop is in the center of the air gap, the flux divides equally between the two outer legs inducing equal and opposing voltages in the two coils. The net output signal, therefore, is zero.

If the conducting loop is moved away from the center of the air gap as shown in Figure 2-6, the flux distribution is altered by the circulating current induced in the loop. This results in less flux flowing through the coil toward which the loop was moved and more flux flowing through the opposite coil. Accordingly, the voltages are unbalanced, and the net output represents the loop position. The loop acts as a flux inhibitor due to the circulating currents induced in it which oppose the flux of the primary excitation.

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124 Ardnt, John P. and Gardner P. Wilson, "An Electro-Mechanical Transducer With Unusually Low Reaction Force," Brush Instruments, Division of Clevite Corporation.

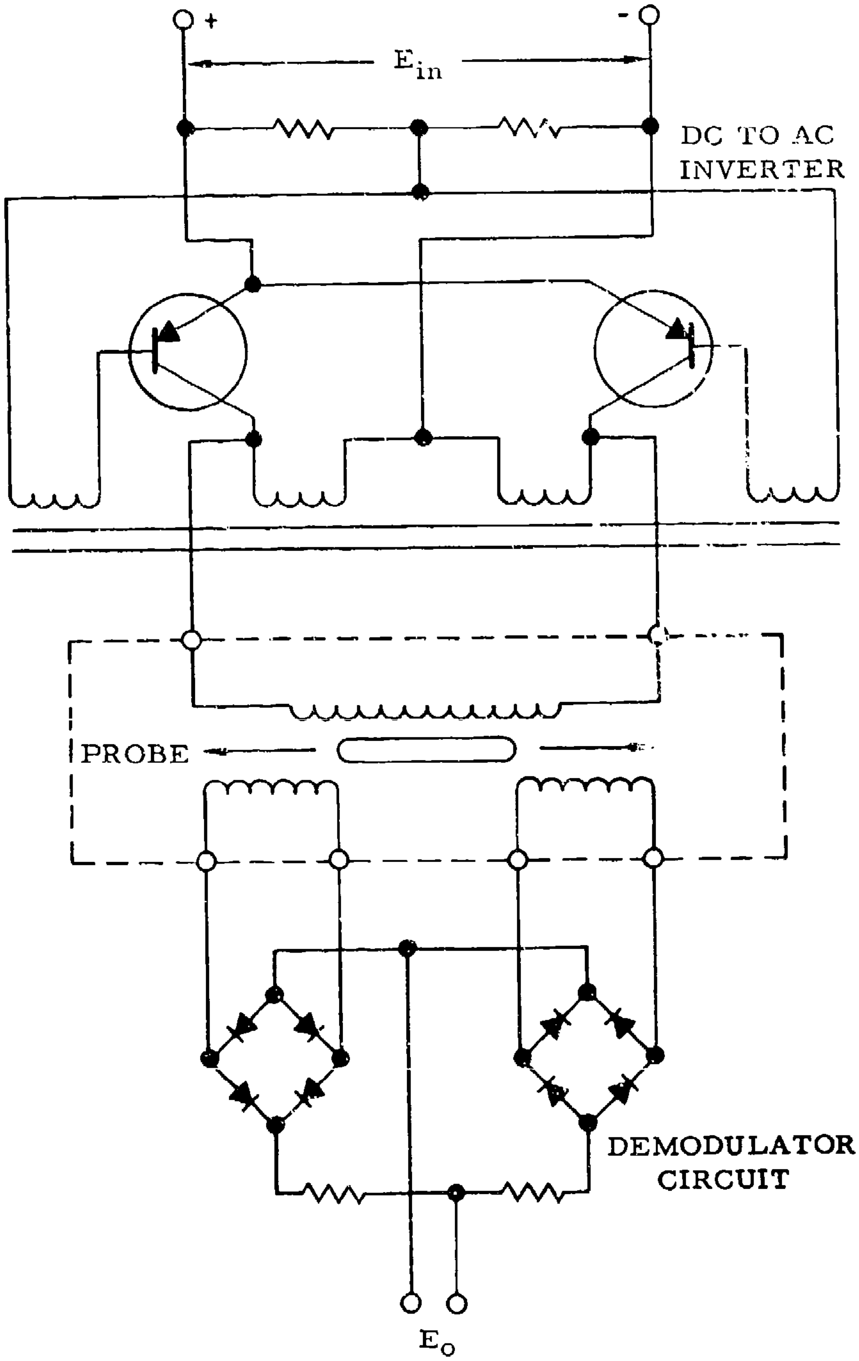

Fig. 2-4. Transistorized Circuitry

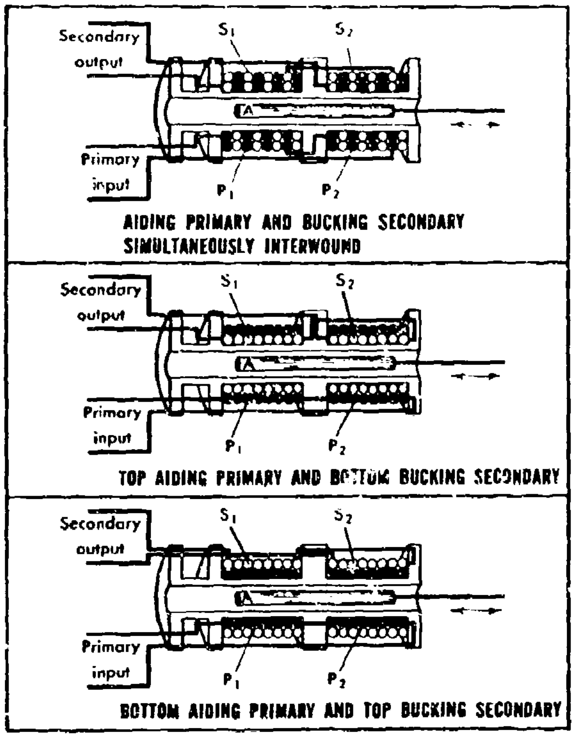

Fig. 2-5. Four-Winding Configurations

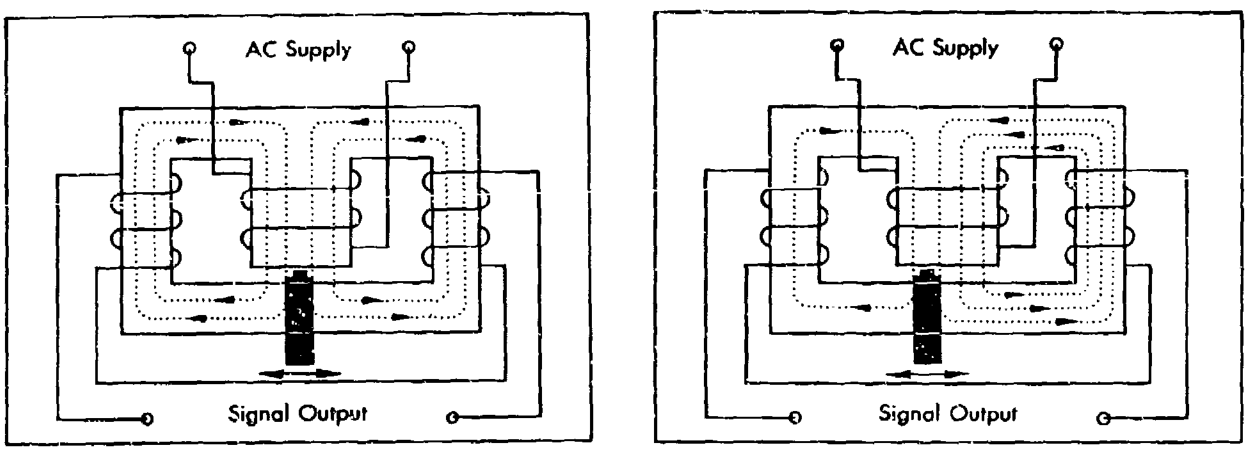

Fig. 2-6. Flux Distribution of the Metrisite

When the air gap is uniform, the output is very nearly a linear function of loop position over a distance approximately equal to the width of the central leg of the core. The major source of error is fringing of the flux. In designs requiring the best possible linearity, the slight error due to fringing may be eliminated by proper shaping of the air gap.

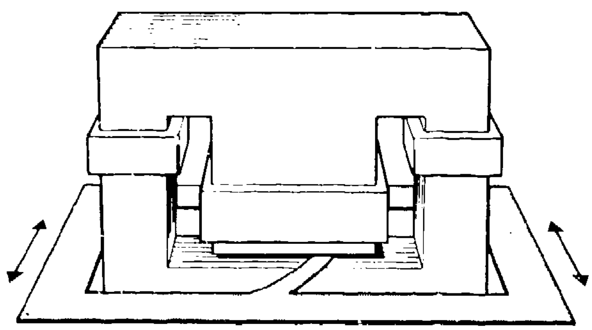

Fig. 2-7. Armature Designed for Non-Linear Input-Output Function

Variants of the H and E core magnetic configurations have been employed in differential transformers. Figures 2-8 and 2-9 depict their basic armature movements.

The underlying principle of operation is the large variation in the reluctance of the magnetic circuit resulting from relatively small armature movements. These reluctance changes in turn vary the coupling between the primary and secondary windings, thus producing an output voltage.

The sensitivity of the E and H core design is exceedingly high, but the output is necessarily non-linear. Another undesirable characteristic is the appreciable magnetic pull between the armature and pole pieces.

(2) Linearity and Linear Range (Ref. 125)

The output voltage of an air core differential transformer is a linear function of core displacement within a certain range of motion. In other words, within this range, a graph of output voltage

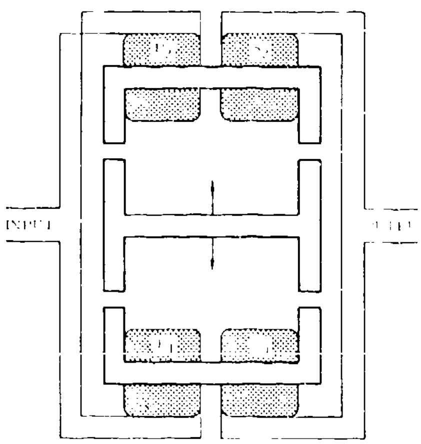

Fig. 2-8. H Core Differential Transformer

125 "Notes on Linear Variable Differential Transformers," op. cit., p. 5.

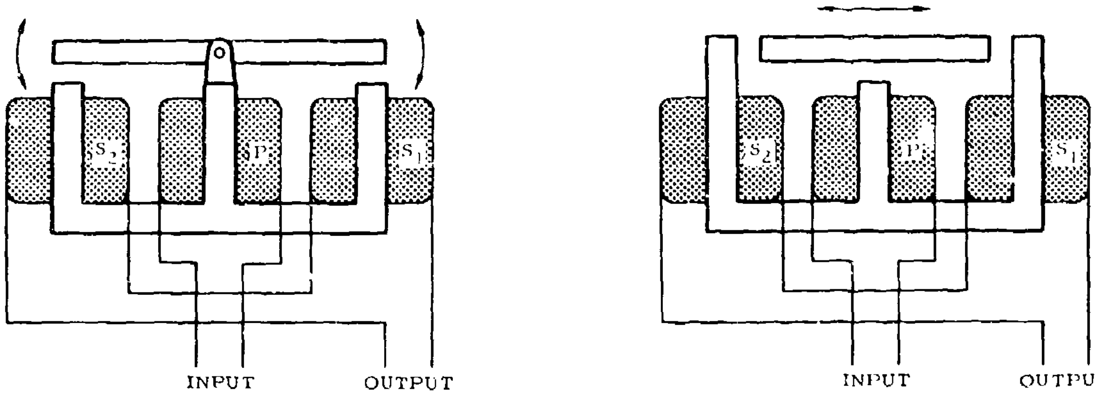

Fig. 2-9. E Core Differential Transformer

versus core displacement is essentially a straight line. Beyond this range, the graph starts to deviate from a straight line.

The degree of linearity within the linear range is defined as the maximum deviation of the output curve from the "best fit" straight line passing through the origin, expressed as a percentage of the output at nominal range. For example, if the output is 1.25 volts when the core is displaced from the null to the limit of the nominal range and the maximum deviation of the output curve from the straight line through the origin that best fits the curve is ±0.005 volts, the linearity is ±0.005/1.25 or ±0.4%.

Unlike the potentiometer, the differential transformer may be connected to a wide variety of load impedances from infinity down to an impedance of the same order as its differential secondary impedance. In many applications, the load may be given any value in this range with only small effect on linearity or linear range.

(3) Sensitivity and Output (Ref. 126)

The rated sensitivity is usually stated in terms of millivolts output per 0.001 inch core displacement per volt input (commonly written mv out/0.001"/volt in.). In a particular application, the input voltage may have a constant specified value so that sensitivity is often simply

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126 Ibid., p. 5.

described in millivolts (or volts) output per 0.001 inch core displacement. As voltage sensitivity varies with frequency, except in some designs over a limited frequency range, the frequency should be stated when specifying sensitivity. The actual output voltage for a given core displacement is determined by multiplying the sensitivity by the displacement in thousandths of an inch, then multiplying this product by the input voltage.

Instead of specifying sensitivity as described above, some users prefer to specify the output voltage produced at rated input voltage with the core positioned at one end of the rated linear range, more simply stated as the nominal full-range output.

Sensitivity and output generally increase with frequency, particularly in the low frequency portion of the range specified for a particular differential transformer. In some designs, the output variation with frequency may disappear for limited frequency ranges and particular load conditions.

(4) Resolution (Ref. 127)

The output voltage variation of the differential transformer is stepless. Therefore, the effective resolution depends entirely on the minimum voltage or current increment which can be sensed by the associated electrical system. The output may readily be resolved to within 0.1% of the full-range output by a suitable null-balance indicating or servo system such as that shown in Figure 2-10.

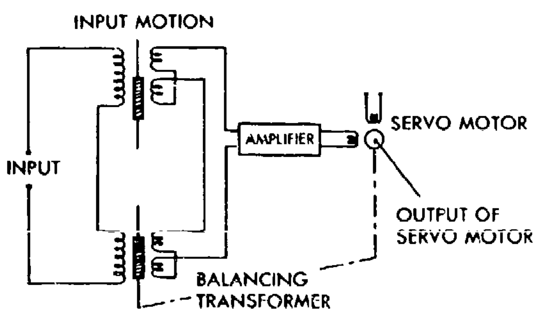

Fig. 2-10. Null Balance Circuit

127 Ibid., p. 7

(5) Excitation (Ref. 128)

The fundamental inductive arrangement of the differential transformer with a straight movable magnetic core can be designed for operation at any ac frequency in the range from below 60 cps up into the radio frequency region (one megacycle and beyond). However, standard transformers for laboratory, military, and industrial application are readily available for operation in the 60 to 20,000 cps range.

When the transformer is used to measure static displacements or to sense linear motion which does not include oscillatory components above approximately 6 cps, the common 60 cps power frequency is generally convenient. The 400 cps aircraft power frequency is widely used and highly suitable for many applications.

Accurate response to vibration and rapid mechanical movement requires the use of an excitation frequency at least ten times the highest frequency present as a component of the mechanical motion, preferably higher.

Many differential transformers have been designed for a conservative nominal input rating of 6.3 volts. Low power at this voltage is readily obtained from standard filament transformers and regulated power sources commonly supplied as components for electronic equipment.

The excitation power required to produce useful sensitivity in different types of transformers varies with transformer size and application. In many applications, this power is only a fraction of a watt. In practice, this power is usually limited by the maximum hot spot temperature produced within the primary winding under the maximum ambient temperature condition of the particular application. Due to the high reluctance of the magnetic path, core saturation generally does not occur with any current value which would not eventually overheat the primary winding.

When a differential transformer is excited at a fixed voltage, the primary current will vary downward with increasing frequency. As the heating effect is proportional to the square of the current for all practical purposes, the maximum input voltage may be

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128 Ibid., p. 7.

increased at higher frequencies by the amount required to maintain the primary current at a fixed value, up to the absolute maximum voltage limit for the winding and circuit insulation.

A constant-current power source, rather than a constant-voltage source, is often preferable for accurate operation, particularly when using an input level which produces a substantial temperature rise in the transformer. A constant-current source eliminates any output variation directly due to the normal primary resistance variation with temperature. This primary resistance variation is important at low frequencies, but may be insignificant at high frequencies where the impedance is principally inductive.

(6) Phase Characteristics (Ref. 129)

The phase angle of the output voltage with respect to the input voltage has two values differing by 180°, depending on whether the core is on one side of null or the other. When not otherwise specified, the phase angle is usually understood to mean the one which is closer to zero.

Generally, the phase angle, as defined above, is between -20° and +75°, depending on the type of transformer, the frequency, load, and other factors. An approximate calculation of phase angle is fairly simple. Taking the input voltage as the reference, the phase of the primary current is the angle whose tangent is $-2\pi f L_p/R_p$, where f is frequency, L_p and R_p are the known values of primary inductance and resistance respectively, and the negative sign indicates that the current lags the voltage. The electromotive force generated in the secondary, leads the primary current by 90°; hence, the phase of this emf is readily calculated. If the output load is a very high impedance, the output voltage is practically equal to the emf both in amplitude and in phase. If not, the phase of the output voltage appearing across the load can be calculated by elementary ac circuit theory if the secondary resistance and inductance are known.

The phase angle calculated by the above simplified procedure is only approximate because it ignores the "reflected impedance" of the secondary circuit which modifies the primary impedance. However, because of the loose coupling between primary and secondary, this effect

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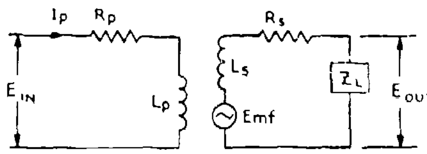
129 Ibid., p. 8.

is small except possibly at high frequencies. The effect of winding capacitance, which has been ignored but which is always present to some extent, may also become appreciable at high frequencies.

An equivalent circuit, based on the simplifying assumptions mentioned above, is shown in Figure 2-11.



NOTE: Emf leads I_P in phase by 90°.

R_S = secondary resistance
L_S = secondary inductance
Z_L = load impedance
I_P = primary current
R_P = primary resistance
L_P = primary inductance

Fig. 2-11. Equivalent Circuit (Simplified)

Displacement of the core causes a shift in the output phase angle, but this shift is usually very small (of the order of 1°) within the linear range.

Normally, as the core passes through the null point, the output phase changes abruptly by 180°. However, under unusual conditions of high minimum balance voltage (or "null" voltage), such as might be caused by masses of metal located close to the transformer, the 180° phase reversal is not abrupt but takes the form of a gradual phase shift in the vicinity of the null point. At the null point, the phase angle differs by 90° from the two phase angles obtained at appreciable distances on both sides of null.

The phase relationships mentioned in the preceding paragraph are illustrated in Figure 2-12. The vector OP represents the input (primary) voltage. OS_1 and OS_2 represent the output voltage at the two opposite ends of the linear range. OS_o represents the minimum output voltage, which occurs at the "null" point. The other solid-line vectors represent the output voltage for intermediate displacements. The magnitude of the minimum voltage OS_o has been greatly exaggerated in the figure for purposes of illustration. The dotted line represents the output of a perfectly balanced differential transformer having zero minimum voltage, OT_1 and

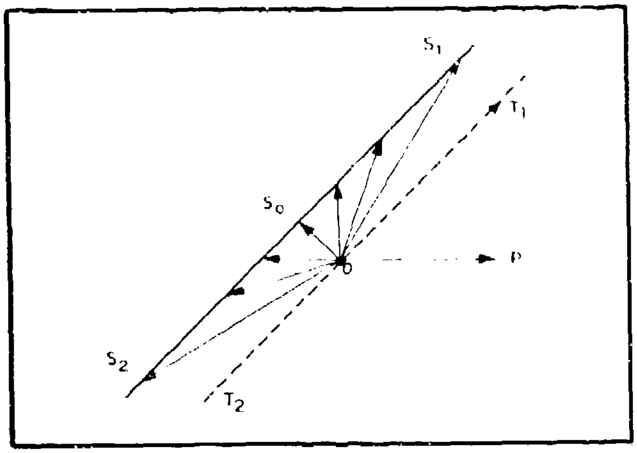


Fig. 2-12. Output Phase Angles for Various Core Positions (amplitude of null voltage exaggerated for clarity)

OT_2 being the output voltages at the ends of the linear range. The line passes through zero and the phase changes abruptly by 180° at that point.

In many applications, the output phase angle is of no importance. In some applications, however, it is desirable to make the angle small or zero. Generally speaking, an increase in frequency will reduce the phase angle, and in some cases, the desired phase angle may be obtained by suitable selection of frequency.

In other cases, a simple circuit modification can be used effectively to give zero output phase angle. Typical corrective circuits are shown in Figure 2-13. The choice of circuit and of component values, depends on the type of transformer, the application in which it is used, and the characteristics desired, such as maximum sensitivity, minimum variation of phase with frequency, or minimum variation of phase with core displacement.

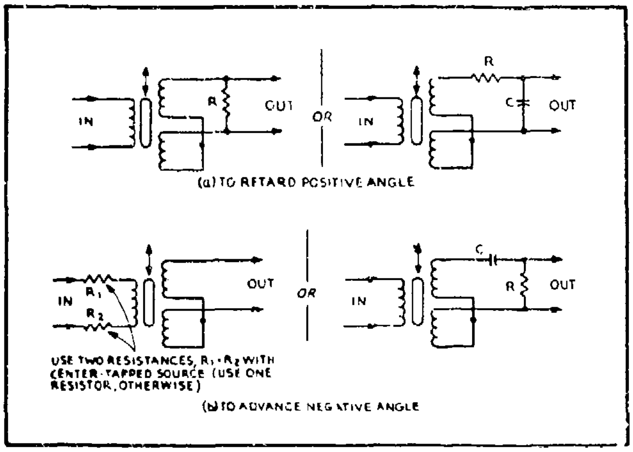


Fig. 2-13. Practical Circuits for Reduction of Phase Angle

b. Synchros (Ref. 130)

Synchros are motor-like devices to translate angular position to electrical signals or vice-versa. Although the class of transducers which includes synchros and resolvers is not, in a strict sense, a part of the telemetry transducer group of instruments, it is a transducer class which is often involved in a telemetry system in a secondary manner. This can be illustrated by the hypothetical application illustrated in Figure 2-14. In this application, a missile control system functions according to the position of a certain surface. The control system operation is based on the position, θ, which is obtained from a synchro transmitter-control transformer follow-up servo and the sine of the angular position, sin θ, which is obtained from the resolver. It is desired to telemeter both of these input functions to some location as a check on the control system operation.

The resolver output, E_1 sin θ, is an ac voltage (usually 60 or

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130 "Synchros," Electromechanical Components and System Design, Vol. III (February, 1959), p. 51.

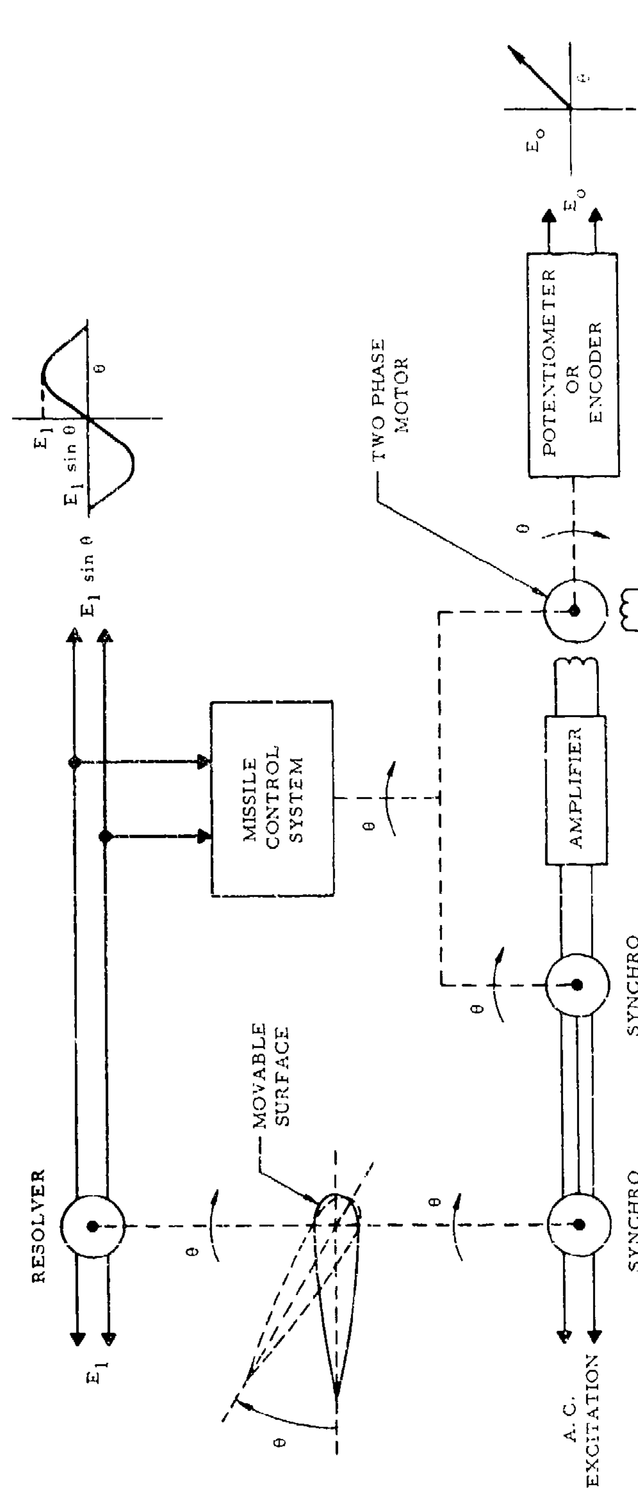

Fig. 2-14. Synchro-Resolver Telemetry System Application

400 cps) which can be used directly to drive a voltage controlled oscillator of an FM/FM telemetry system. Since the synchro control transformer presents a mechanical output, this must be converted by the use of a second transducer (potentiometer or encoder) to obtain an electrical output which is a function of the input angle, θ. This electrical output can then be used to drive a voltage controlled oscillator for FM modulation or the encoder output can be used for a PCM/FM telemetry system.

(1) General

There are two essential types of synchros. The first of these, the simplest but least commonly used, is the group of torque synchros which can transmit angles directly without the use of additional servomechanism components. Where light loads are to be angularly driven, such as pointers and remote indicators, torque synchros are satisfactory. However, because angular error depends upon output shaft loading, they are inadequate for appreciable loads. Furthermore, their nature requires that they operate quite hot and at high flux densities, introducing angular inaccuracies. These units will not be considered further in this text.

More important are the control synchros, including three basic types: the synchro control generator, the control differential generator, and the control transformer. These are interconnected by simple wiring, with electrical energy applied only at the input terminals to the synchro control generator. The synchro generator converts its shaft angle to a set of electrical voltages. The differential generator, energized by the synchro generator, has output windings which in turn, energize a control transformer. The shaft angle of the differential generator adds to, or subtracts from, the input shaft setting of the control generator. The control transformer receives signals from the generator or the differential generator and, by means of a servomechanism, is driven to a null depending upon the shaft position of generator and differential generator. The control transformer has a two-terminal output which develops an error signal proportional to the sine of the angle of its shaft displacement from correspondence with generator and differential generator angles. This error is amplified to drive a servo motor which in turn drives the control transformer and any other additional load to a null position.

Control synchros are used with a servomechanism. Output energy is supplied by the servomechanism, permitting torque multiplication.

Figure 2-15 shows a typical angle transmission system incorporating a transmission generator, a differential generator, and a control transformer, as well as a servomechanism for driving the output angle. The figure indicates how this system works. Where required, additional control transformers can be connected to the generator or differential generator, or additional differential generators may be inserted in chains. A great variety of practical configurations may be assembled for specific use. Because of transient coupling as well as increased errors, torque synchros are seldom used with control synchros.

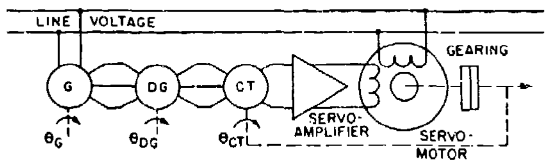

Fig. 2-15. Synchro Angle Transmission System Incorporating a Synchro Generator, Differential Generator, and Synchro Control Transformer. The generator translates the line voltage excitation to a flux field whose orientation with respect to its three-phase secondary winding is determined by its shaft angle, θG. The single-phase field in the DG primary, which is the resultant of the three input currents, may be reoriented by adjustment of θDG. The CT is positioned to correspond to θG - θDG by the servo-system shown in the figure.

(2) Principle of Operation

Although variations exist, Figure 2-16 shows the common arrangement of magnetic circuits within a synchro. The stator incorporates a three-phase winding. (However, it should be remembered that only single-phase line power is applied.) The generator rotor may be a salient pole or conventional wound rotor, incorporating a single phase winding. Sometimes a short-circuited winding is applied at right angles to the main rotor winding to improve accuracy. However, its role is not

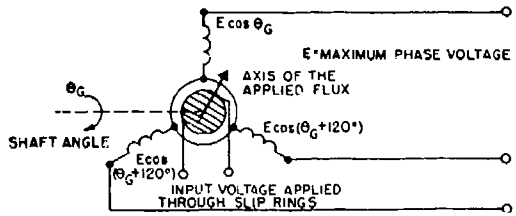

Fig. 2-16. Synchro Simplified Diagram. This depicts how the input voltage applied to the rotor winding of a synchro generator induces secondary voltages in the three-phase output winding which vary sinusoidally with shaft position.

fundamental and it will not be considered here further.

The differential generator has a three-phase stator and a three-phase rotor winding. It is distinguished from both the generator and the control transformer by the three slip rings necessary to make coupling with the output brushes. Windings are arrayed on the motor-like magnetic lamination stacks and generate fields similar to those shown in Figure 2-16. This figure, in simplified form, shows the ideal operating condition in a synchro transmission system. Because each synchro represents a balanced load, additional synchros on the system do not change the basic theory of operation.

(3) Accuracy

(a) Static Errors

Synchro accuracy is affected by design and manufacturing errors. Transmission accuracy can vary from about 5 to 30 minutes of angle, with instances of both better and worse accuracy occurring. Accuracy is generally improved in larger units, or units operating at higher frequency, such as 400 cycles rather than 60 cycles. The more important factors determining accuracy are the roundness and symmetry of the magnetic circuit elements, and the uniformity and balance of the three-phase windings. Factors tending to produce unbalance or dissymmetry introduce errors. Iron in the magnetic circuit is of highest importance, requiring use of high nickel alloys with very high permeability.

These alloys are carefully annealed and assembled so as to eliminate strains or grain effects which tend to introduce dissymmetry.

Since the windings generate the magnetic fields, layout of the coils is extremely important. The choice of slot combination, turns per slot skew, and the shape of salient pole structures, are design factors affecting the sinusoidal flux distribution.

The nature of the angular error, particularly the frequency of repetition in a 360° period, is a function of its origin. Table 2-2 tabulates the errors occurring in a synchro system, identifying the sources. Figure 2-17 shows a typical error curve for a synchro transmission system.

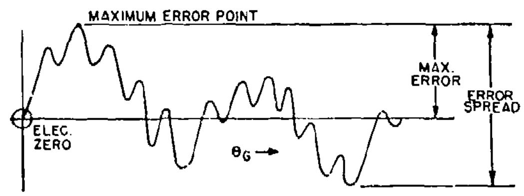

Fig. 2-17. Typical Error of Synchro Transmission System. For discussion of the composition of this error curve, see Table 2-2.

(b) Velocity Errors

In addition to the static errors discussed above, synchros are subject to an error due to rotational velocity. Thus, if the rotors of a generator and control transformer are aligned to produce essentially zero error output, and if the rotors are then rigidly coupled together, so that there can be no relative motion between them, and if then the two synchros are rotated together, a voltage will appear at the control transformer terminals. This voltage will consist in part of components due to the static errors discussed above, but there is also a steady component that increases with speed. Hence, if the two synchros are used in a servo system that tends to null the in-phase component of the output voltage. the output tends to run slightly behind the input when a constant velocity input signal is applied. This velocity error is an addition to the error normally found in servo systems having velocity lag. These output errors occur in the high-speed synchros of a multi-speed synchro

Table 2-2. Error Components in Synchro Transmission Systems

The error pattern of a synchro-transmission system (error versus shaft position) may be analyzed into its Fourier Components. These will have a periodicity which may be expressed in cycles per complete synchro revolution. In general, the pattern of quadrature residual voltage will have a similar appearance, the relative magnitude being determined by the source of the error.

Error Comp.	Origin	Possible Cause
One cycle	Rotor eccentricity	Manufacturing inaccuracies, purely random.
Two cycle	Unbalance in 3-phase circuitry	Stray capacitance or resistance in line, elliptical stator air-gap, stray line coupling. Random occurrence.
Six cycle, also 12, 18, etc. cycles	Non sinusoidal flux waves.	Common error pattern in many synchros due to harmonics generated by the windings. Uniform error pattern for specific synchro designs.
Slot Errors	Non-sinusoidal flux-wave.	Error pattern due to slot combinations in synchros. Less important with increased number of slots. Minimized by proper skewing. Uniform error pattern for specific synchro designs.

system. They are significant when the synchro system is operating higher than about 1/3 of synchronous speed.

c. Electrical Resolvers (Ref. 131)

(1) General

Electrical resolvers are small motor-like components in the same family as synchros. They differ from synchros in that they have two input windings and two output windings on the rotor and stator respectively. The windings on each member are distributed at right angles to one another so that individual rotor windings and stator windings do not interact among themselves. The resolver is represented schematically as shown in Figure 2-18. The unit generally has four slip rings and brush assemblies providing electrical contact to rotor windings. For transducing application, only one set of slip rings may be required, or in many instances where angular travel is limited, pigtail connections may be provided.

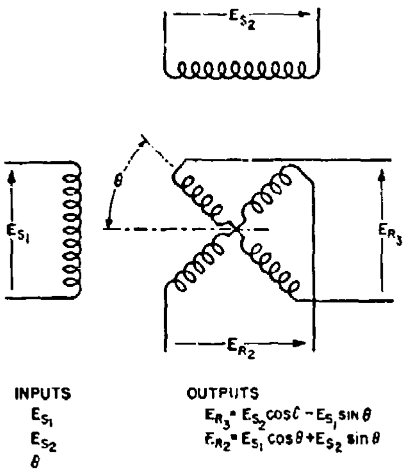

Fig. 2-18. Schematic Representation of the Electrical Resolver

When a resolver primary winding is excited, voltage is generated in the opposing windings, varying as a sinusoidal function of shaft position. Since the windings are distributed at 90° to one another on

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131 Ibid., pp. 54-56.

both rotor and stator, output voltages constituting sine and cosine functions of shaft angle are generated. Simultaneous application of voltage to both primaries causes a resultant magnetic field whose magnitude corresponds to the square root of the sum of the squares of the separately applied voltages and whose angular orientation depends on the vector resultant of the separate applied voltage vectors. Because of these properties, a resolver is directly applicable to problems involving trigonometry, such as the conversion of coordinates, rotation of coordinates and in most computing applications where trigonometric functions appear. Resolvers are especially suited to fire-control problems in which a good deal of the computation is necessarily based upon trigonometry. Here, however, we will not consider these applications of the resolver, but rather its use as a transducing element.

Many variations of the resolver exist. Resolvers may serve as four-wire synchro systems where accuracies of the order of several minutes are required. Large diameter units, having many poles, which can be regarded either as resolvers or synchros, sometimes called "pancake units," are frequently found as transducer-type sensors. Sixty-cycle resolvers as well as 400-cycle resolvers are available, the former being considerably larger than the latter. Resolvers are also available for application up to many kilocycles.

(2) Errors

The resolver is particularly well-suited to measurement of a limited angular travel. The absence of resolution steps makes it possible to detect motions of the order of several seconds of arc. Many errors that arise as a result of mechanical irregularities such as eccentricity of rotor and stator, ellipticity of the critical magnetic air gap surfaces, or similar departures from ideal, may be balanced out over a small angular range by careful trimming and adjustment of scale factor. This is feasible because errors from these sources vary slowly and may be assumed constant or linearly varying over small ranges.

For small angle applications, the most serious error is shift in the axis or null point. The axis drifts as a result of changing conditions, primarily temperature. Drift of the order of one minute of arc is not uncommon. Where the total angular span is of the order of several degrees, drift may be a significant portion of the overall error.

Additional angular errors resulting from slot harmonics within the resolver air gap also occur. Although by careful winding design, it is possible to reduce most air gap harmonics to zero, slot harmonics can be reduced just so far, the minimum error depending roughly on the inverse square of the number of slots. In small resolvers with few slots, these harmonics may introduce as much as a minute or two of error with consequent angular inaccuracy. Scale factor or output voltage per unit displacement may vary, introducing additional error.

While scale factor may be trimmed to an exact value for a given set of operating conditions, variations in temperature, line frequency, and to some extent input voltage, will cause changes. Temperature errors, the most troublesome, are frequently compensated by the use of thermistors. In many instances, although not particularly in transducer applications, booster amplifiers employing feedback compensation are used to maintain constant input-output phase shift and scale factor over varying conditions.

A particularly troublesome source of error for small angular ranges is residual voltage, occurring in all electromagnetic components. Residual voltage appears at the null position and determines the maximum gain to which the control amplifiers may be set without saturation. Residual voltage includes both fundamental and harmonic components. Various circuits have been devised to cancel out the former. Harmonics are minimized by selecting optimum magnetic materials, operating these at very low flux densities, and maintaining large air gaps. Filtering provides further attentuation, but attention must be given to avoid time delays which can affect system stability.

Table 2-3 summarizes the errors that can occur in electrical resolvers. These are typical of errors found in all magnetic-type pick-offs. This classification of errors is required to prepare an accurate specification by avoiding over-specifying certain aspects of performance while ignoring others. For example, note from the table the effect of varying input voltage on the transmission ratio of the resolver. This varying input voltage varies magnetic core permeability and consequently, the main coupling reactance, changing the resolver transmission ratio. While booster compensation can correct this, boosters are bulky and expensive and introduce considerable circuit complexity. However, other methods of resolver compensation cannot correct this particular error.

Table 2-3. Sources of Errors in Electrical Resolvers

Misalignment of axes of coils, due to imperfect geometry
Slowly varying errors, due to imperfect geometry.
Variation of transmission ratio with applied voltage.
Temperature errors, primary copper resistance.
Frequency errors, transmission ratio and phase, as with any transformer.
Angular inaccuracy, resulting from imperfect sinusoidality of windings.
Application errors, due to unbalanced or non-standard loading, primary impedance unbalance, pick-up, etc.

Figure 2-19 shows the variation in transmission ratio as a function of applied voltage for a typical resolver. At very low input voltage where the magnetic material permeability approaches its

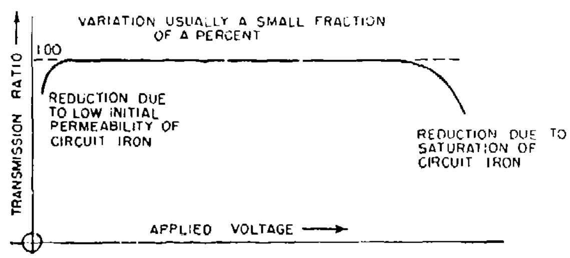

Fig. 2-19. Variation of Transmission Ratio with Applied Voltage as a Result of Iron Nonlinearity

initial value, transmission ratio variation is most pronounced. At the high voltage extreme, saturation sets the operative limit. By restricting voltage range and using very high permeability alloys, such as Supermalloy, it is possible to hold these errors to acceptable limits. Where transducers operate at essentially constant voltage, this problem does not exist.

Note that the resolver has an error unique to itself, namely the alignment of the axes of the different coils. These axes should be precisely 90° apart. Achievement of an exact 90° is very difficult. Auxiliary trimming coils have been used with some success. Axis alignment is affected by line voltage variations as the changing magnetic core permeability causes a corresponding though small shift in the flux axis. Because axis alignment is difficult to control, and because not all resolver applications require four active coils, it is often economical to classify production resolvers in accordance with the number of properly aligned windings. Thus, a grade A resolver might have excellent alignment while a grade C would have poorer alignment of axis. Grade C units might be used where only one input and one output winding are required, so that axis misalignment causes no deterioration whatever in quality of performance. This is strictly for economy, and complicates stocking of spare parts.

d. Induction Potentiometers (Ref. 132)

(1) General

Induction potentiometers belong to that family of rotating components that include synchros and resolvers. They are distinguished by their single input winding and single output winding. Where additional windings are provided, they are used solely for balancing impedances, and do not have a directly functional role. Although they are used principally as a computing element, we consider here their use only as a transducer. Their linear output voltage versus shaft angle characteristics provide high accuracy, good stepless resolution, and particularly good performance in comparison with conventional potentiometers for equivalent diameters and angles of rotation. An important characteristic of the induction potentiometer to note is that its output impedance is not constant with the result that loading affects angular accuracy.

Figure 2-20 shows the performance of the induction potentiometer indicating the nature of the magnetic field, the relationship between input and output windings, and one technique whereby a linear function of shaft angle is achieved. Other combinations of windings, not described here, achieve a similar result. Although capable of infinite rotation, the induction potentiometer operates over a limited angular

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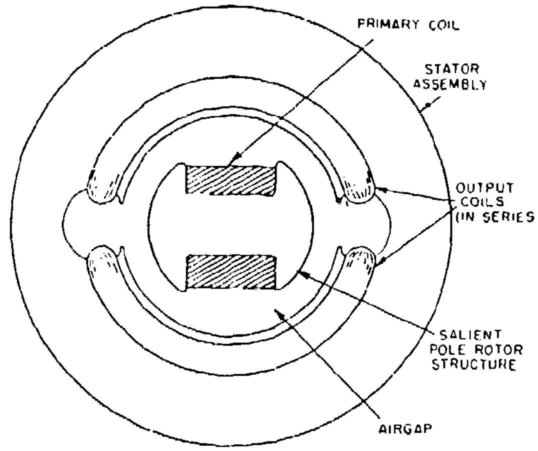
132 Ibid., pp. 58-59



(The air gap flux is distributed uniformly in the salient region of the rotor structure. Thus, in the position shown, the primary to secondary coupling will vary linearly with rotor shaft position.)

Fig. 2-20. Relationship Between Windings and Magnetic Field in an Induction Potentiometer, to generate a linear voltage-displacement characteristic.

range. The circuit shown in the figure covers a useful angle of about 60 to 70°. Accuracy deteriorates badly for angles beyond this value. Induction potentiometers have been devised with operating angles up to double this figure, but they exhibit other performance limitations.

(2) Refinements

To illustrate more specialized techniques required for good performance in transducers of this type, note the following in Figure 2-21:

1. To achieve a square flux wave, a special booster coil is provided in the center of the main coil to raise the flux level where

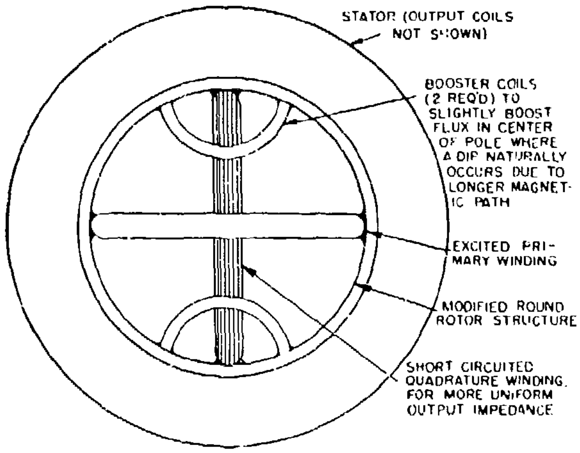


Fig. 2-21. More Complex Induction Potentiometer Circuit, showing refinements required for good performance.

the normally greater reluctance of the magnetic path tends to produce a dip in flux density.

2. A pair of balanced secondary windings is provided 90° apart. By symmetrically loading these windings even when only one output is required, the primary impedance becomes far less sensitive to loading with greatly reduced linearity error from this source.

3. A symmetrical second winding is provided on the primary structure 90° from the input winding. This winding is normally short-circuited providing some of the benefits described below.

With a single primary coil, the output impedance varies from a minimum, when the coil is coupled directly to the output

winding for maximum output, to a maximum 90° away. Use of a short-circuited quadrature winding minimizes impedance variation so that the output impedance is a maximum at 45°. Variation in output impedance is reduced by this means by 3, 4, or 5 to 1. Where a limited angular travel of about 45° is required, a properly distributed winding at 90° to the main winding, distributed approximately sinusoidally, results in an output impedance independent of shaft position.

An additional benefit of the shorted quadrature windings on the primary structure (both in the induction potentiometer and the resolver) besides maintaining output impedance constant, is the reduction in flux axis shift due to housing distortion, mechanical dissymmetry, temperature changes, and aging. The shorted quadrature winding cancels quadrature flux resulting from dissymmetry by generating flux bucking currents.

(3) Applications

Application of the induction potentiometer is very similar to application of the resolver as a transducer, except that here, as a result of the linearity characteristics, a much wider angular range can be covered. Induction potentiometers possess long life, very low noise, a stepless output, and can operate at very high speeds. Very important application in the computing field is not covered here since we are confining our topic to transducer applications. As with resolvers, the effect of changing air gap reluctance, as a result of iron permeability variations with temperature or flux level, the effect of frequency shift, temperature effects on the copper winding, etc., are very similar to those previously discussed. Thermistor compensation is a convenient method for correcting temperature errors in induction potentiometers.

e. Electronic Displacement Transducers

(1) Moving Anode Transducer

The plate current in a space-charge-limited vacuum tube is a function of the electrode geometry. Small displacements can be measured with a triode system as illustrated below. A device of this type is the Mechano-Electronic Transducer, RCA Tube 5734, illustrated in Figure 2-22. The cathode and grid assembly are held in a fixed position within a vacuum-tight envelope, the anode is supported by a rod which extends through the center of a thin metal diaphragm sealed

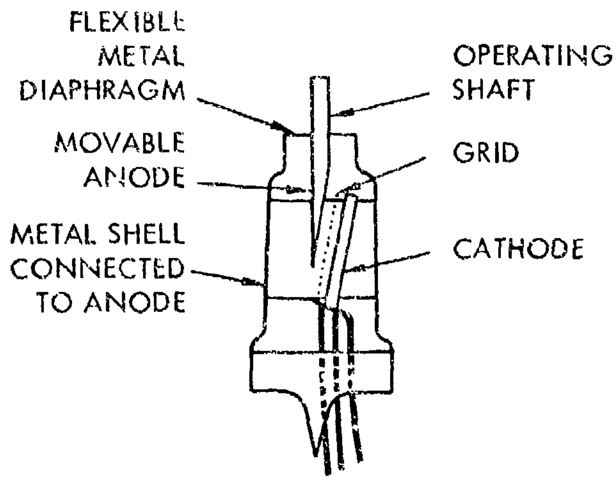


Fig. 2-22. Moving Anode Transducer

to the tube envelope. An angular displacement of this rod leads to a variation of the plate current. The transfer characteristic is linear within about 2%. The maximum permissible displacement of the rod is ±0.5° about the zero position. For this displacement, a torque of 13.3 g-cm is required. The moment of inertia of the moving system is 3.4 mg-cm^2. The frequency response is limited by the mechanical resonance of the part of the plate shaft within the tube, which is about 12,000 cps. The tube is generally operated in the bridge arrangement shown in Figure 2-23.

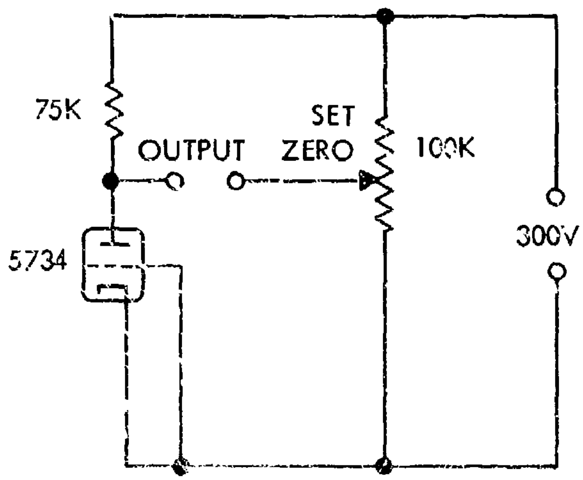


Fig. 2-23. Circuit For RCA 5734 Transducer

The maximum displacement of the anode rod by 0.5° results in a variation of the output by ±20 volts. Mechano-electronic transducers are delicate, both mechanically and electrically.

(2) Ionization Transducer (Ref. 133, 134)

A dc voltage of considerable magnitude arises between two electrodes in contact with a gas discharge caused by a radio frequency field. This principle gives rise to a transducer system which permits conversion of mechanical displacements and capacitance changes into electrical signals.

A glass tube filled with gas at a pressure of about 10 mm Hg and containing two electrodes is brought into an electrical high-frequency field between the plates P_1 and P_2 of a capacitor, as shown in Figure 2-24. If the field is sufficiently high, a glow discharge will arise in the tube. The two electrodes A and B act as probes in the discharge; their potential is determined by the space potential of the plasma surrounding each electrode and by the rf potential induced by their capacitive coupling to the plates P_1 and P_2. In the symmetry position, the net charges of both electrodes are equal, so that their potential difference is zero. Outside of the symmetry position, the charges are different for each electrode and give rise to a dc potential difference. The transfer characteristic, i.e., the output voltage E_0 versus the displacement S, is illustrated. Potential difference can reach values of more than 100 volts, and $\Delta E_o / \Delta X$, can reach values up to several volts per micron of displacement. For technical reasons, operation between 0.1 and 10 mc is recommended. Accurate frequency stability is not required for the operation of the transducer.

The preceding circuit arrangement is useful for displacements up to about 1 mm. Other arrangements are possible for movements up to several inches.

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133 Decker Technical Bulletin No. 01, The Decker Corporation, Bala-Cynwyd, Pennsylvania.

134 Lion, Kurt S., "Mechanic-Electric Transducer," The Review of Scientific Instruments, Vol. 27, (April, 1956), pp. 222-225.

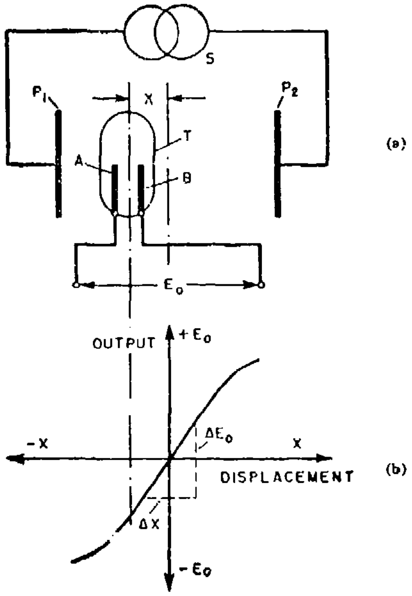

Fig. 2-24. Ionization Transducer

A circuit for measurement of capacitance is shown in Figure 2-25. This circuit and a variety of probes are commercially available from the Decker Corporation, Bala-Cynwyd, Pennsylvania. The transducer is excited by two external electrodes. The internal probe electrodes are connected to one of the external electrodes through a differential capacitance. Every variation of this capacitor causes a corresponding change (as high as +60 to -60 volts) of the out put voltage. Capacitance changes of 10^{-15} Farads or motions of 10^{-6} inches are readily measured.

By capacitively coupling the appropriate probe to the sensor configuration in question, measurements of the following parameters may be made: capacitance, pressure, vibration, proximity, rotation, weight, liquid level, speed, temperature, thickness, strain, force, humidity, and displacement.

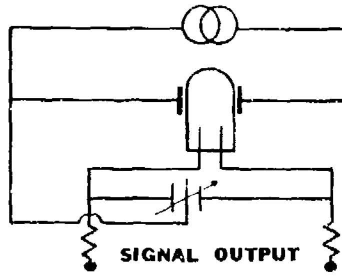

Fig. 2-25. Capacitance Measuring Circuit

(3) Radiation Tracking Transducer (Ref. 135)

This transducer is a single-element photovoltaic device that detects position of visible to near infrared radiation simultaneously in two axes. Coupled with a lens system, this solid state component is capable of detecting angular position of a radiation source. An example of its operation is depicted in Figure 2-26. A uniform spot of

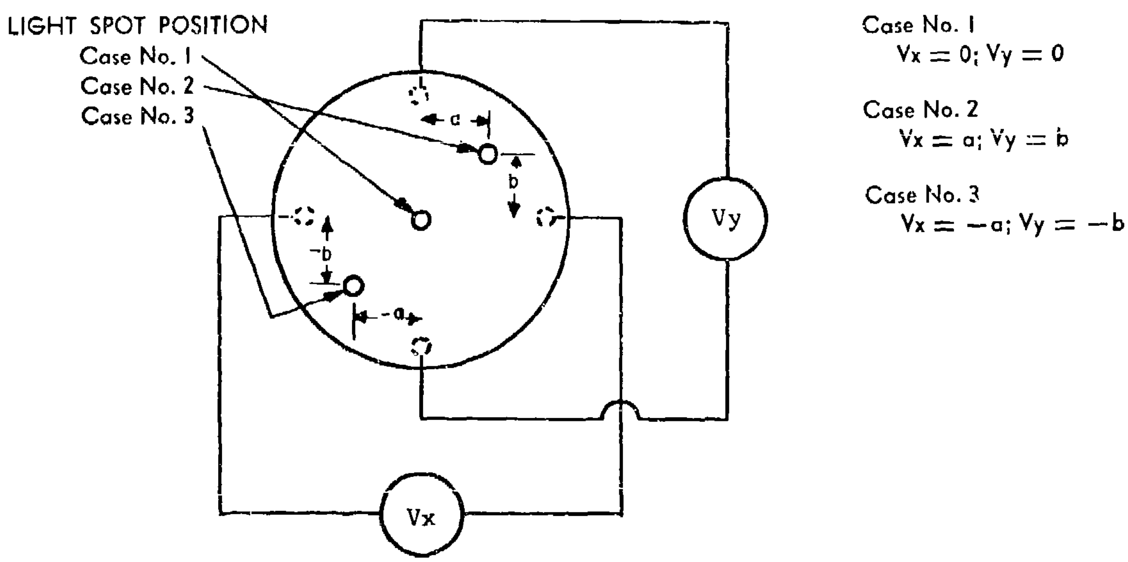

Fig. 2-26. Example of Radiation Tracking Transducer Operation

135 "Radiation Tracking Transducer XY-20," (company brochure), Micro Systems, Incorporated, Pasadena, California.

light focused on the center of the cell produces zero output. When the spot is positioned off center in the X or Y axis, a voltage output is produced at the X or Y terminals proportional to the degree of displacement. When used with a light source and a reflecting or masking member, the transducer can be adapted to such applications as vibration in two co-ordinates, acceleration in two co-ordinates, pressure, angular position, strain, and liquid or gas flow.

f. Mechanical-Optical Transducers (Ref. 136

Mechanical displacements can be converted into electric signals by optic-electrical means, for instance, by an arrangement consisting of an illuminated slit and a photoelectrical transducer; the moving object obscures a part of the slit and causes a variation of the light intensity reaching the photoelectrical transducer, and hence a variation of the transducer output.

An arrangement of this type which may be used for the conversion of rotary displacement into a digital output is shown schematically in Figure 2-27. An optical system produces a number of parallel light

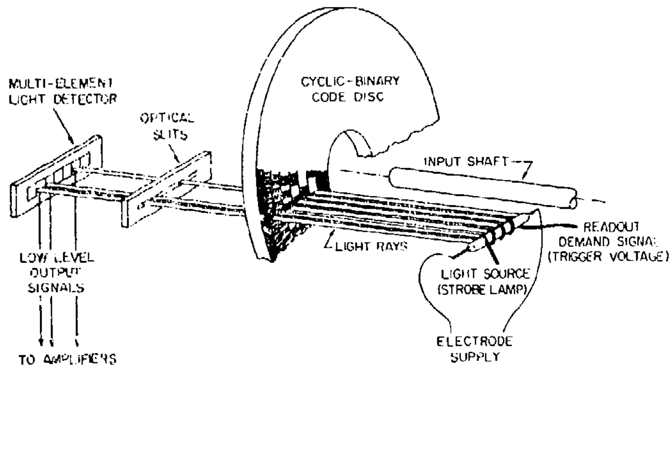

Fig. 2-27. Shaft Position Encoder

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136 Lion, Kurt S., Instrumentation in Scientific Research (Electrical Input Transducers), New York: McGraw Hill Book Co., Inc., 1959, pp. 89-90.

beams which are directed upon corresponding photo transducers. The light beams traverse an encoder disc with transparent and opaque segments. Depending upon the position of the disc, some of the light beams will reach the photo transducers and cause an output signal; the result appears in binary digits (e. g., 1, 1, 0).

An encoder disc with thirteen concentric arrays of segments, for thirteen-digit information, is shown in Figure 2-28. A disc of this type gives a different output for each of the 2^{13} possible configurations,

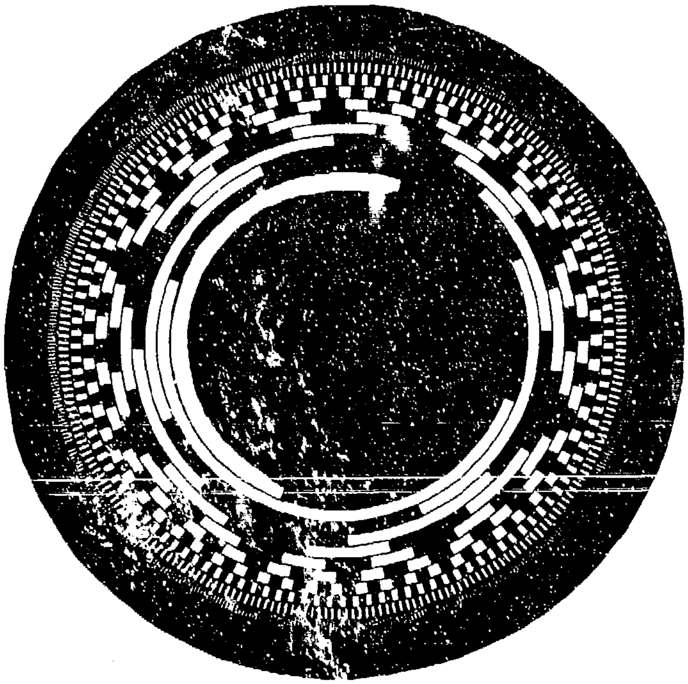

Fig. 2-28. Encoder Disc for 13 Digits

i. e., it furnishes information of the angular-disc position with an accuracy of 360°/8912, or an angle of about 0.044°. Systems of this type have been built with discs of 10" diameter having up to seventeen concentric segments. An accuracy as high as ten seconds of arc has been obtained. Instantaneous reading of rotating discs is accomplished by pulse operation of the light source.

g. <u>Electrolytic Potentiometers (Ref. 137, 138)</u>

These devices sense displacement from the horizontal and are sometimes referred to as electrolytic switches and gravity-sensing electrolytic potentiometers. Their basic construction consists of a small sealed cup with two or more electrodes in contact with an electrolyte which partially fills the cup. Two configurations are shown in Figure 2-29.

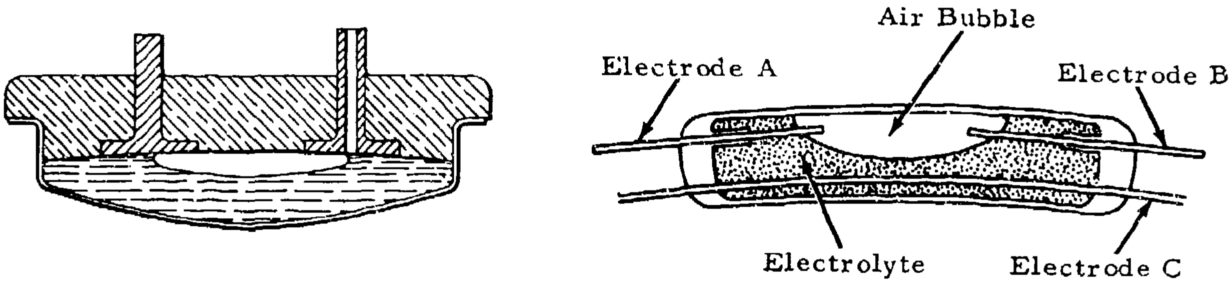

Fig. 2-29. Electrolytic Potentiometers

In the level position, the electrolyte covers an equal area of each electrode. As the switch is displaced from true horizontal, the amount of electrolyte covering the electrodes increases on one side and decreases on the other, creating a differential resistance or conductivity. When a given ac voltage is applied across the unit, a differential current flow is created through the electrodes, proportional to the deviation from level.

Two single-axis potentiometers may be mounted at right angles to one another in order to reference the horizon in two planes; however, the two-plane feature can be built into one unit by employing four electrodes. Operational schematics of single-axis and dual-axis units are shown in Figure 2-30.

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137 Product Data Sheet 118-3, Lear, Incorporated.

138 EP 1012 Data Sheet, Hamlin, Incorporated.

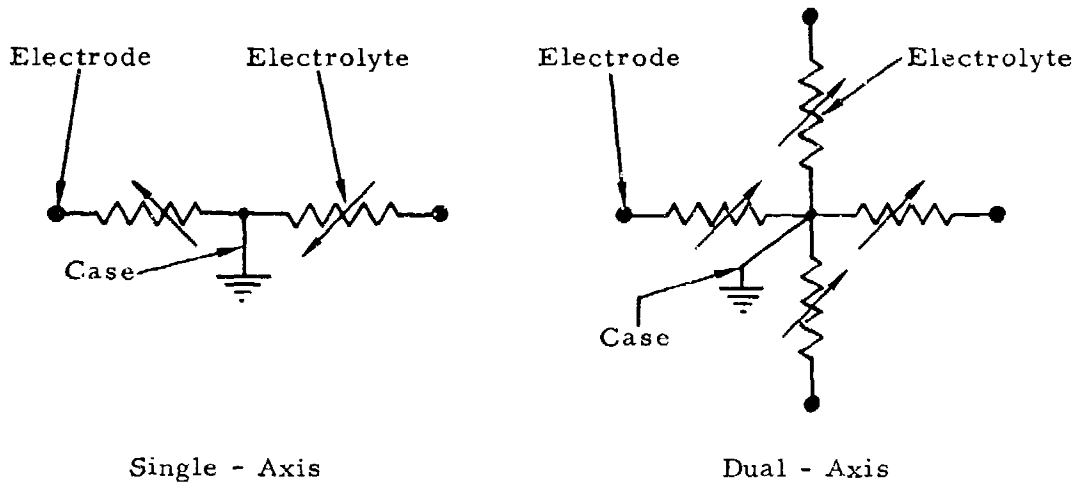

Fig. 2-30. Operational Schematics of Electrolytic Potentiometers

The electrical rating of such units is determined principally by their ability to dissipate heat, and the amount of bubbling at the electrodes that can be tolerated. As the applied voltage is increased, bubbling at the electrodes increases, and an electrolytic pull operates on the air bubble to decrease the stability of the potentiometer resistance, particularly near the zero tilt angle.

When dc is used, the electrolyte slowly polarizes, causing a delay in reaching a stable condition. In general, the operation is much better when ac is used.

2-3 MEASUREMENT OF STRAIN

a. Introduction (Ref. 139)

In telemetry engineering, the measurement of strain is performed through use of electrical strain gages. Therefore, this discussion is limited to such gages and excludes all purely mechanical methods for determining strain in materials and structures.

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139 Aronson, M. H. and R. C. Nelson, Strain Gage Instrumentation, Pennsylvania: Instruments Publishing Co., Inc., 1958, pp. 1-5.

The strain gage has importance as a telemetry transducer for two reasons. First, it is a basic transducer in its own right for measurements of strain. Second, numerous other transducers, notably the pressure gauge and accelerometer, often employ a strain gage as the electrical pickoff. Since this discussion is primarily concerned with strain measurements, the use of strain gages in other types of transducers is not covered in the following paragraphs.

Strain gages are transducers that are applied to the surface of materials in order to sense the strain of the material. The strain gage is elongation sensitive; that is, its electrical properties change proportionately to the elongation of the gage. Strain elongation (of the gage and the member on which it is mounted) is usually small as long as the applied stress does not exceed the elastic limit for a material. Stress is, by definition, the applied force (F) divided by the cross-sectional area (A) of the member:

$$\text{Stress} = F/A \qquad (2\text{-}2)$$

An applied stress produces a strain (dimensional change) in the material. The relationship between stress and the resulting displacement is defined as Young's Modulus(E) where:

$$E = \text{unit stress}/\text{unit strain} \qquad (2\text{-}3)$$

With stress expressed in pounds per square inch and strain in inches per inch, E has a value of 30,000,000 for steels. Thus, a stress of 15,000 psi in a steel member produces a strain of only 0.0005 inch per inch of length. If it is desired to measure stress of 4,000 psi with an accuracy of 1%, the strain gage must be sensitive to an elongation of 1.3 millionths of an inch per inch of gage length.

The most common form of strain gage consists of a short length of small-diameter (approximately 0.001") wire of high electrical resistance. To keep the gage length short, the wire runs the length of the gage several times. To simplify its mounting and to protect it, the wire is cemented between two thin pieces of paper. To apply the gage, it can be cemented to the member to be tested; this is a bonded resistance-wire strain-gage.

Recently, the semiconductor or "solid state" strain gage has become available. This operates on the same piezoresistive effect which

applies to metal strain gages. This effect is the name given to the change in electrical resistivity of a material due to applied stress. Scientists at Bell Telephone Laboratories and the Case Institute of Technology several years ago noted that when a semiconductor crystal is subjected to tension or compression, it undergoes a sharp change in resistance. In 1953, the piezoresistive coefficients of Germanium and Silicon were determined and found to be extremely high. (Gage factors up to 175 as compared to 2 to 5 for metallic wires.)

Strain, in engineering usage is defined:

Strain = change in length/original length

$$S = \Delta L/L \qquad (2\text{-}4)$$

Strain gages indicate strain indirectly -- that is, the length change is measured in terms of a resistance change. The method, although indirect, is precise -- accuracies to 0.1% can be achieved. Coupled with this accuracy is great application flexibility.

When the test member is strained, so is the bonded gage. As the wire is strained, its electrical resistance changes. This resistance change is directly proportional to the strain in the wire, and the strain in the wire is directly proportional to the strain in the member.

Strain in a test member (S) is defined as $\Delta L/L$. The unit resistance change that the strain produces is defined as $\Delta R/R$. The relation between the unit strain and the unit resistance change is defined as gage factor (G). That is:

$$G = \frac{\Delta R/R}{S} = \frac{\Delta R/R}{\Delta L/L} \qquad (2\text{-}5)$$

The gage factor (G) is the conversion constant between strain and gage resistance, and depends on the type of material used for the strain-gage wire. Manufacturers maintain close control on wire composition, but the measured gage factor, stated on each package, should be used in all calculations. Table 2-4 gives some gage factors and temperature coefficients.

Table 2-4. Typical Average Gage Factors and Temperature Coefficients

Material	Gage Factor	Temp. Coeff. of Resistance ohms/ohm/°C
Advance	2.1	0.0001
Chromel	2.5	
Constantan	2.0	0.00001
Copel	2.4	
Isoelastic	3.5	0.00047
Manganin	0.47	0.00001
Monel	1.9	0.002
Nichrome	2.5	0.0004
Nickel	-12.1	0.006
Phos. Bronze	1.9	0.002
Platinum	6.0	0.003

b. Basic Circuit

The basic strain gage is merely a wire whose resistance is directly proportional to the strain in the wire. When bonded to a member, this effect provides a direct indication of the strain in the member itself. This resistance change is made to yield a useful output by employing the strain gage in conventional resistance measuring circuits.

At its most basic level, this circuit takes the form of a potentiometer as shown in Figure 2-31. However, the most commonly used circuit is that of a Wheatstone bridge.

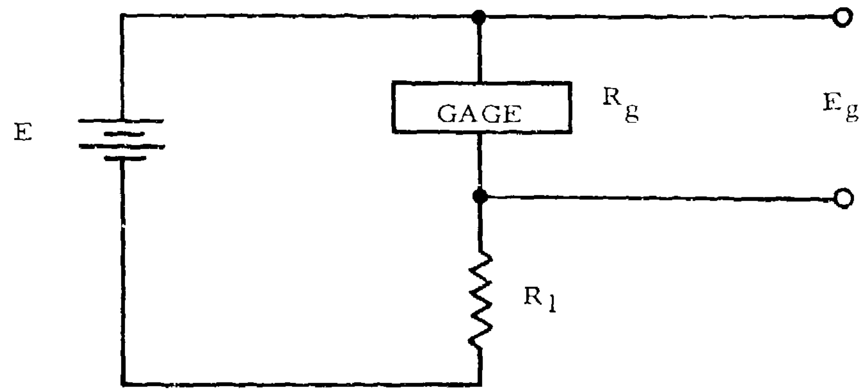


Fig. 2-31. Strain Gage in a Potentiometric Circuit

There are several disadvantages to the potentiometer circuit which make it unsuitable for most applications. Since Δ R_g is small compared to R_g, Δ E_g will be small compared to E_g and its measurement is difficult. The static component E_g may be removed by a bias voltage or capacity coupling; however, neither approach is desirable. The bias voltage represents another error producing factor and the use of a coupling capacitor limits low-frequency response. In this circuit, the temperature coefficient of resistance of the gage and R_1 produce direct errors, another undesirable aspect.

c. Wheatstone Bridge

(1) General

Since the disadvantages of the potentiometer circuit can be eliminated in the Wheatstone bridge, its use has become standardized in the application of strain gages. To obtain temperature compensation from the bridge, two or four active arms are necessary. An indirect advantage of this is the increased gage sensitivity which is obtained through the use of more than one active arm.

Figures 2-32 and 2-33 show the two common Wheatstone bridge circuits in simplified form. R_3 and R_4 of Figure 2-32 are dummy resistors necessary to complete the bridge circuit.

Since slight differences in the resistance of gages or dummy resistors may exist and a small strain unbalance is likely (when the gage is mounted), a method of producing an electrical zero is required. This is accomplished by a balancing potentiometer (R_B) and isolation resistor (R_I) as shown in Figure 2-34. The balance potentiometer must enable the zero output condition ($R_1R_4 = R_2R_3$) to be obtained. A method of adjusting full-scale output voltage, or bridge sensitivity, is desirable and commonly accomplished by the use of a resistor, fixed or variable, in series with the bridge power supply, shown in Figure 2-34 as R_S.

A calibration resistor (R_C) and switch (Sw) are also shown in Figure 2-34. The most desirable method of system calibration from the standpoint of absolute accuracy, is to apply a known input of strain to the instrumented structure. However, this is not always practical for pre-flight and in-flight calibration. Therefore, an electrical calibration is frequently employed by shunting one active arm of the bridge to simulate the known resistance change caused by a particular mechanical input.

An accessory device, usually referred to as a "bridge balance and calibrating unit" has become an integral part of strain gage systems. These devices house the balance potentiometers and sensitivity adjustment resistors for a number of channels (up to 24) in a self-contained unit. Provision for dummy and calibration resistors is also provided. Calibration is accomplished by the switching of calibration resistors across one arm of the bridge. In more elaborate units, this is performed automatically with a stepping switch to provide in-flight calibration. Balance and drive voltage meters are sometimes provided, as well as series or shunt galvanometer damping resistors.

There are two basic applications of the Wheatstone bridge to consider; the case where the bridge output drives a high impedance intermediate load such as an amplifier, and the case where the bridge drives a low impedance measuring device directly, such as a galvanometer.

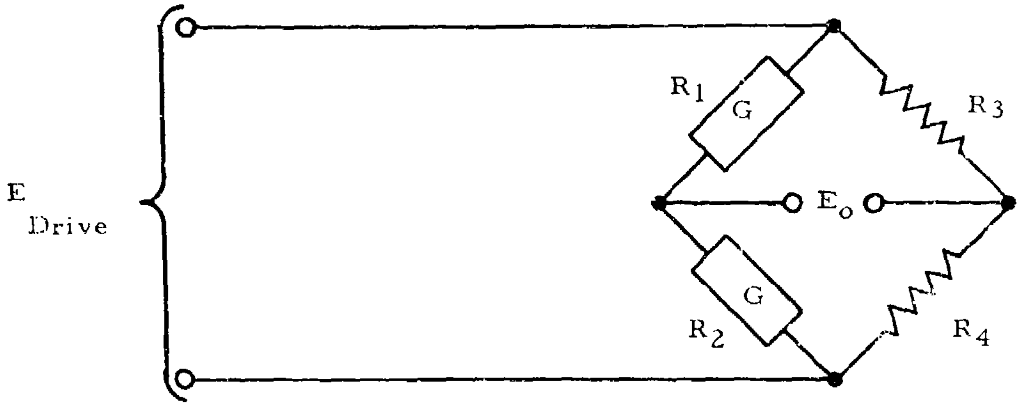


Fig. 2-32. Wheatstone Bridge With Two Active Arms

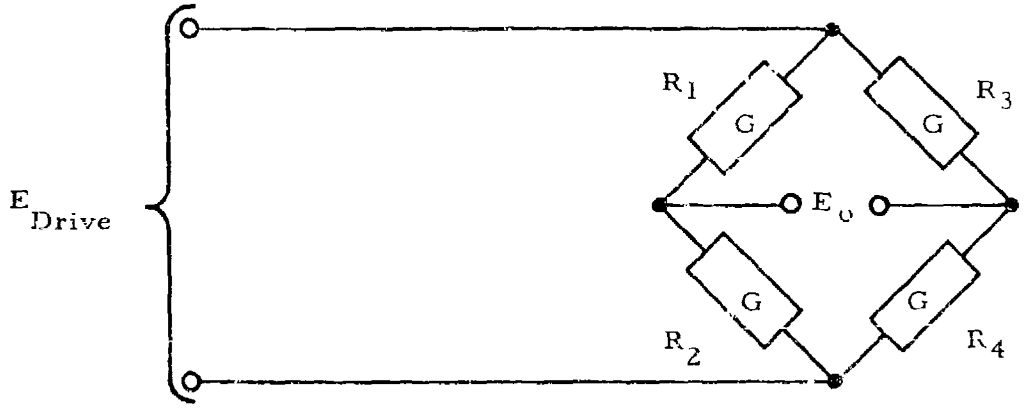


Fig. 2-33. Wheatstone Bridge With Four Active Arms

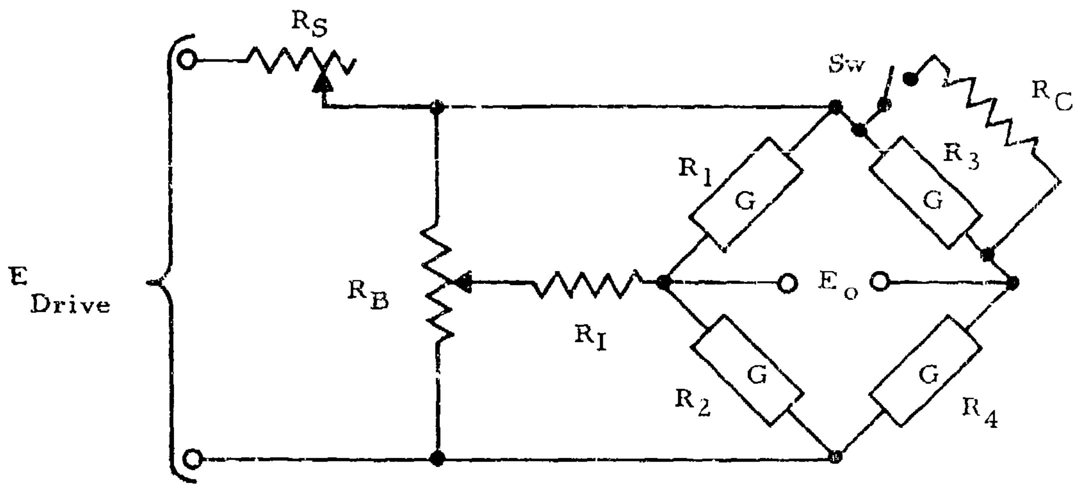


Fig. 2-34. Strain Gage Bridge and External Circuitry

(2) High Impedance Load

The typical high impedance load for a strain gage is a voltage amplifier to provide sufficient output to drive a voltage-controlled subcarrier oscillator or other voltage sensitive telemetry system input. Strain gages are frequently subcommutated, or sampled since the frequency of information is usually quite low. Because it is difficult to directly subcommutate or multiplex the low-level signals from a strain gage, amplification is usually required.

Referring to Figure 2-32, it will be assumed that $R_1 = R_2$ and $R_3 = R_4$. This is the usual case to allow the bridge to be conveniently balanced. In the case of the bridge with four active arms (Figure 2-33), all arms are usually of the same resistance. Gages of matched gage factor and resistance are usually employed.

For two active arms, the open-circuit or high impedance load output voltage from a Wheatstone bridge is

$$E_o = \frac{E}{2}\left(\frac{\Delta R}{R}\right) \qquad (2\text{-}6)$$

where

$R_1 = R_2 = R$

$\Delta R_1 = \Delta R_2 = \Delta R$

E = Drive Voltage

For four active arms, the open circuit voltage is

$$E_o = E\left(\frac{\Delta R}{R}\right) \qquad (2\text{-}7)$$

where

$R_1 = R_2 = R_3 = R_4 = R$

$\Delta R_1 = \Delta R_2 = \Delta R_3 = \Delta R_4 = R$

E = drive voltage

When the above equations are combined with the strain gage equation,

$$G = \frac{\Delta R/R}{\Delta L/L} \qquad (2\text{-}5)$$

a more useful expression for output voltage is obtained:

$$E_o = \frac{GENS}{4} \qquad (2\text{-}8)$$

where

G = gage factor

E = drive voltage

N = number of active arms

S = $\Delta L/L$ = unit strain

(3) Low Impedance Load

When a bridge is used to directly drive a galvanometer or other low impedance device, the output voltage equations must be modified. Galvanometers having sensitivities of greater than 1 millivolt per inch deflection are common; therefore, multichannel oscillographs represent useful strain gage recorders. However, galvanometer coil resistances are very low, usually less than the resistance of the strain gage itself. Their load effect on bridge output must be taken into consideration. This can be done by employing the following equations which apply to the case of four equal resistance arms.

$$E_L = \left(\frac{R_L}{R_L + R}\right) E_o \qquad (2\text{-}9)$$

or

$$I_L = \left(\frac{1}{R_L + R}\right) E_o \qquad (2\text{-}10)$$

where

E_L = voltage across the load

I_L = current through the load

R_L = load resistance

To maintain optimum galvanometer frequency response, the galvanometer damping must be correct. In many cases, through careful selection of the strain gage and galvanometer, the damping offered by the characteristic resistance of the bridge itself will be correct. In this case, no additional series or shunt galvanometer damping resistors are required. However, if it is necessary to employ damping resistors, their effect on bridge output must be taken into account.

(4) Calibration Resistor

As previously mentioned, a calibration resistor may be employed. By shunting one arm of the bridge, any percentage of full-scale output can be obtained. It is general practice to calibrate at the level of maximum anticipated output, or at normal full-scale output. Calibrating in this manner can minimize errors due to drive voltage drift and galvanometer sensitivity inaccuracy. The following equations give the value of R_C in terms of equivalent strain:

$$S = \frac{1}{G}\left(\frac{R}{R + R_C}\right) \qquad (2\text{-}11A)$$

or

$$R_C = R\left(\frac{1 - GS}{GS}\right) \qquad (2\text{-}11B)$$

It is frequently desirable to obtain the value of R_C in terms of output voltage:

$$E_o = \frac{E}{4}\left(\frac{R}{R + R_C}\right) \qquad (2\text{-}12A)$$

or

$$R_C = R\left(\frac{E}{4E_o} - 1\right) \qquad (2\text{-}12B)$$

(5) Special Applications

Certain special purpose devices have been designed to directly accept strain gage outputs and to provide an internal drive voltage. The drive voltage in these cases is usually ac and consequently, the impedance of the bridge is not always purely resistive. However, the preceding equations generally apply since reactive components are usually balanced.

A relatively common telemetric device which operates directly with a Wheatstone bridge circuit is the strain gage subcarrier oscillator. These are usually phase shift oscillators wherein the bridge output provides the frequency controlling feedback. Some versions of this device have automatic compensation for the effects of shunt capacity in the bridge and leads, while others require external neutralization.

There are also time-division telemetry systems which will directly accept strain gage transducer inputs. The multiplexer of these systems is designed to provide an ac drive, usually synchronized with the sampling rate, through the use of a polyphase transformer with separate drive windings for each input channel. External neutralization is not usually required.

One of the most common ac techniques is the suppressed carrier system. This approach usually provides the same results as a conventional bridge and dc amplifier (i. e., dc output at a relatively high level); however, it avoids the difficulties of dc amplification. In this system, an ac drive is provided and the bridge output is amplified, detected, and filtered to produce the desired dc output.

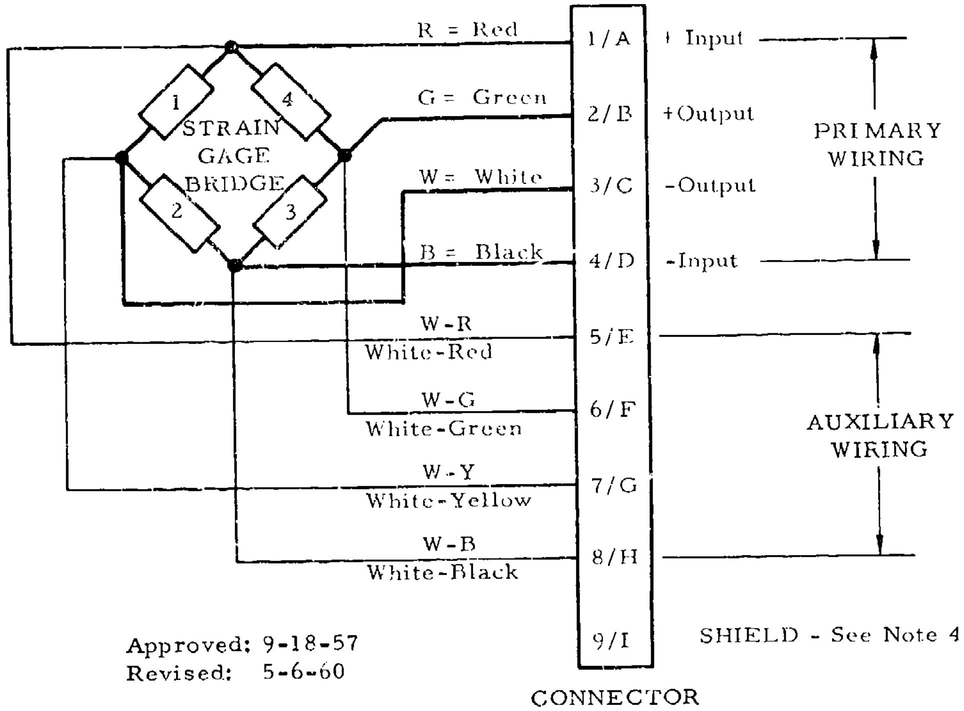
d. Wiring Standard

Figure 2-35 shows a standard wiring diagram and color code for strain gage type transducers, recommended by the Western Regional Strain Gage Committe (1052 West Sixth Street, Los Angeles 17, California). This recommended standard has evolved from an extensive survey of users and manufacturers and reflects the preferred color coding of a majority of the major users.

2-4 MEASUREMENT OF PRESSURE

a. Force Summing Devices

From basic physics, force is equal to the product of pressure and the area over which pressure is exerted. In the telemetering of pressure and vacuum, certain mechanical elements are generally used to convert the applied force into a displacement; however, the displacement is not always a linear function of the force (or pressure). These mechanical elements are often referred to as "force summing devices." Those which are commonly used for converting pressure into displacement are listed below



1. The direction or position of the function producing a positive output signal shall be indicated on all transducers. *

2. The bridge elements shall be arranged so that functions producing positive output will effect increasing resistance in arms 1 and 3 of the bridge.

3. Wherever possible, tension, elongation, increasing pressure, or other generally accepted positive quantities shall produce positive output signals. Exceptions: compression load cells and vacuum gages.

4. For shielded transducers, pins 5, 7 and 9 shall be shield terminals for 4, 6 and 8 wire systems respectively.

* The following markings are suggested:
- +↕ Tension Load Cells, Universal Load Cells, Micrometers, etc.
- +↕ Compression Load Cells
- → Accelerometers and Flow Meters
- ↑ + ↓ Torque Transducers
- \+ Differential Pressure Cells at the port where the higher pressure causes positive output signals

Fig. 2-35. Transducer Wiring Standard for Resistance Strain Gage Systems. (Prepared by the Western Regional Strain Gage Committee.)

and illustrated in Figure 2-36.

1. Diaphragm
    a. Flat
    b. Corrugated
    c. Capsule
2. Bellows
3. Bourdon Tube
    a. Circular
    b. Twisted
4. Straight Tube

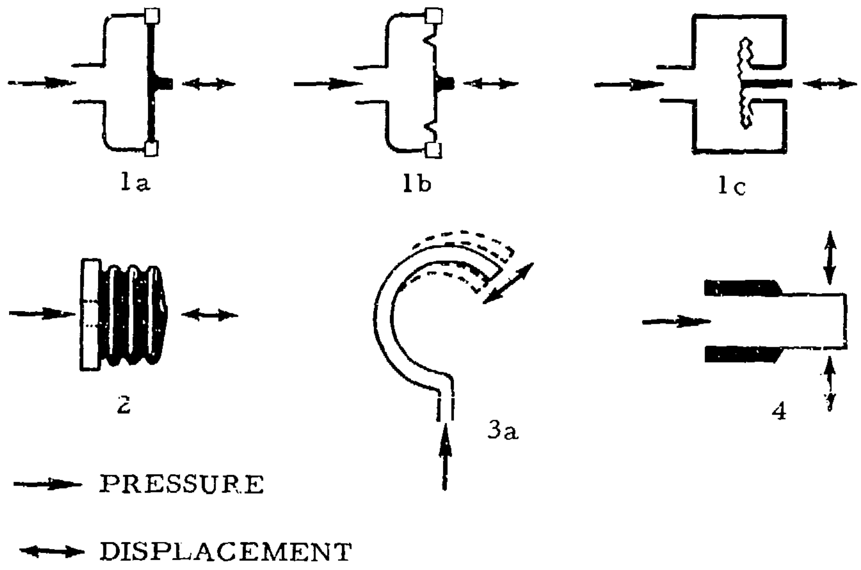


Fig. 2-36. Force Summing Devices

(1) Diaphragms (Ref. 140)

A diaphragm is a flat or convoluted surface, usually circular, bonded at its outer circumference to a circular support or another

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140 Pressure Transducing and Instrumentation Techniques, Vol. 1, Book 1, WADD Technical Report 59-743, p. 113. AD 251111

diaphragm. The convoluted form usually consists of a number of convolutions of radial symmetry. Such diaphragms can be used singly or in pairs. When used in pairs, by bonding together two diaphragms at their outer circumference, the resultant assembly is called a capsule. One or more capsules may be used together to obtain a desired stroke. The deflection of a capsule is slightly more than twice a single diaphragm, since the rim is not restrained radially.

(2) Bellows (Ref. 141)

A bellows is a cylindrical pressure element which contains a large number of convolutions along the length of the cylinder. Relatively stiff end plates are usually provided to close off the ends of the bellows and make it airtight. The cylindrical convolutions provide an infinite number of springs along the length of the bellows, providing a much lower spring rate along its length than across the diameters.

As the pressure inside the bellows is increased, it tends to expand along the lines of least resistance. In this case, the line of least resistance is along the length of the bellows. The internal pressure acting on the end plates tends to increase the length of the bellows until balanced by the stresses along the length of the cylindrical springs. Since the spring rate opposing the increase in diameter is large with respect to the spring rate opposing the increase in length, the small increase in diameter is neglected in most cases and the increase in length utilized.

(3) Bourdon Tube (Ref. 142)

A Bourdon tube is a length of tubing whose cross-section is some shape other than circular (usually flat-oval) and whose length has been deformed into a curve predominantly in the plane of the smallest cross-sectional dimension. The simpler and more common form of Bourdon tube has a constant radius of curvature along its active length and covers an arc length of less than 360°. In some cases, the tube is fixed at one end and the stroke measured at the other end, and in other cases the tube is fixed at the middle of its active length and the movement between the two free ends measured. In order to get more active length of tube and therefore more stroke, the tube can be made in the form of a spiral with a

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141 Ibid., p. 114.

142 Ibid., p. 110.

continuously variable radius of curvature and an arc length of well over 360°, or in the form of a helix with a constant radius of curvature and again an arc length of well over 360°. Both of these designs have the same cause of change in radius of curvature as the plain Bourdon tube, but since they have more active length, the free end of the tube will travel over a greater distance and give more stroke.

Since the cross-section of a Bourdon tube is not circular, the introduction of internal pressure will tend to deform the cross-section into a circle. In doing so, the smallest cross-sectional dimension will increase and the largest will decrease. A length of tube in its unpressurized state has a given radius of curvature of the centroid of area along its length and a given cross-sectional thickness along that radius. As a result, the innermost line and the outermost line have given lengths. If the tube is pressurized, these points will move away from the centroid of area by some amount. The innermost line moving closer to the center of curvature will tend to get shorter and will have compressive stresses set up along its length. The outermost line will tend to stretch and will have tensile stresses set up along its length. These stresses are resisted by the material of the tube to some extent and result in the opening up of the radius of curvature and a movement of the free end of the tube.

(4) Straight Tube (Ref. 143)

Also known as the "hollow tube," this is the only force summing device in this discussion which has an initial circular cross-section and therefore cannot deform into this shape. Instead, while under pressure, the walls of the tube stretch and the diameter increases. The deflection that is measured may either be the diameter increase or the increase in circumference.

b. <u>Conversion of Displacement to an Electrical Analog Signal</u>

Force summing devices provide a displacement as a result of their input pressure and it is necessary that this be converted to an electrical parameter which can be fed to, or sensed by, the input circuitry of a telemetry system. The telemetry system may receive an electrical signal or may "see" a change of impedance as a result of the displacement. Although some

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143 <u>Ibid.</u>, p. 111.

methods of measuring displacement have been covered in Paragraph 2-2 of this section, it is the intent of this discussion to provide representative techniques employed in pressure transducers.

(1) Potentiometer Types (Ref. 144)

The bellows and Bourdon tube generally have sufficient displacement, as a result of their pressure input, to be suitable for attachment to the wiper arm of a potentiometer. Changes in the pressure cause a mechanical movement of the bellows or Bourdon tube. This results in a corresponding change in position of the potentiometer's slider. If the potentiometer is supplied with a constant ac or dc voltage, its output voltage also changes. When a bridge circuit is involved, the slider position causes a variation in the ohmic value of one or more active arms.

The potentiometer winding in most cases consists of a tightly wound coil of very fine wire. Its resolution is relatively coarse since it depends on the ability of the sliding contact to distinguish contact with one wire, the bridging of two wires, and then a one-wire contact, as the slider moves across the coil. Windings with spacings of the equivalent to 1,000 turns per linear inch have been achieved. Deposited conducting films on ceramics and glass have been employed in a few pressure transducers to give almost infinite resolution.

Figure 2-37 shows two pressure transducers which utilize wirewound potentiometers (Ref. 145). These transducers require an external voltage source. The output voltage produced by the motion of the wiper arm may be supplied to a voltage controlled oscillator of a FM/FM telemetry system.

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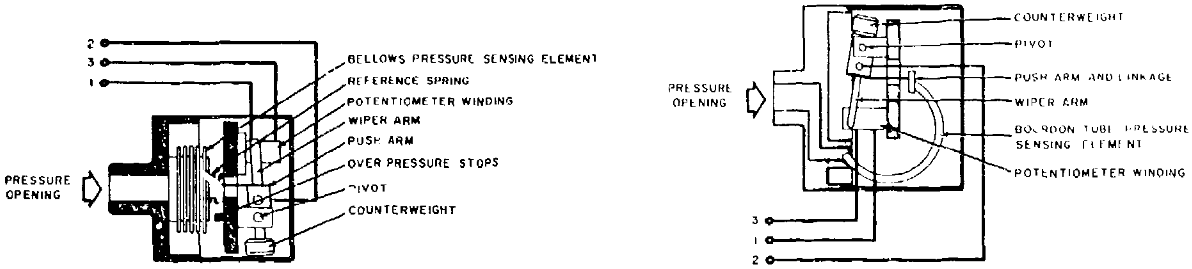
144 Borden, Perry A. and Wilfrid J. Mayo-Wells, Telemetering Systems, New York: Reinhold Publishing Corporation, 1959, pp. 130-131.

145 General Catalog and Transducer Handbook, Technical Bulletin No. 75, Trans-Sonics, Incorporated, November 1960.



(a) (b)

Fig. 2-37. Pressure Transducers with Potentiometer Pickoffs

Advantages and disadvantages of potentiometer type transducers are as follows:

Advantages

(a) High output
(b) Simple and easy to use
(c) Relatively inexpensive
(d) May be used with ac or dc
(e) A wide range of non-linear functions is obtainable
(f) High electrical efficiency
(g) Amplification and impedance matching are gene ally unnecessary
(h) May be used for static or dynamic measurements

Disadvantages

(a) Generally finite resolution
(b) Limited life
(c) Sensitive to vibration
(d) Low frequency response
(e) Relatively large displacements are required
(f) Large actuating force required
(g) Noise increases with wear

(2) Variable Reluctance Type (Ref. 146, 147)

An example of the use of a variable reluctance pickoff in a pressure transducer is one in which a twisted Bourdon tube is the force summing device. This is a length of hollow tubing which has been flattened and twisted about its longitudinal axis. One end is sealed and pressure is applied to the other. The open end is held fixed, but the sealed end is free to rotate as pressure is applied. The tube untwists when the pressure in it is positive and twists when it is negative or when the pressure outside is positive. Thus, it can be seen that the tube will respond to pressure or vacuum applied either internally or externally and to the difference between internal and external pressures. Another variation is to evacuate and seal the pressure element, applying pressure only to the outside of the element, through the transducer case inlet. This is the basis of an absolute pressure pickup. It is also practical to evacuate and seal the transducer case and apply the pressure inside the tube.

A flat magnetic armature may be fastened to the sealed end of the element so that it rotates with it, as illustrated in Figure 2-38. The rotation causes air gaps in an electro-magnetic circuit to change, thereby changing circuit inductances. These inductances may be employed as two active arms of a four-arm bridge as shown in Figure 2-39. Two of these arms are fixed by using the center tapped secondary winding of an oscillator output transformer. The two active arms, shown as L_1 and L_2, are the coils in the transducer. The movement of the armature causes the inductance of L_1 to increase and that of L_2 to decrease as pressure is applied. The instrument is adjusted initially to a balanced condition such that the voltage drop across L_1 is equal to the voltage drop across L_2. This results in an output voltage E_o of zero volts in the absence of an applied pressure. As the armature rotates, the voltage drop across L_1 increases as that of L_2 decreases in proportion to the magnitude of rotation. Half the difference between these two voltage drops appears as the output voltage at E_o. Working into an open circuit, this output voltage is approximately 10% of the input voltage.

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146 Engineering Data Sheet 359-103, Daystrom-Wiancko Engineering Company.

147 Engineering Data Sheet 359-104, Daystrom-Wiancko Engineering Company.

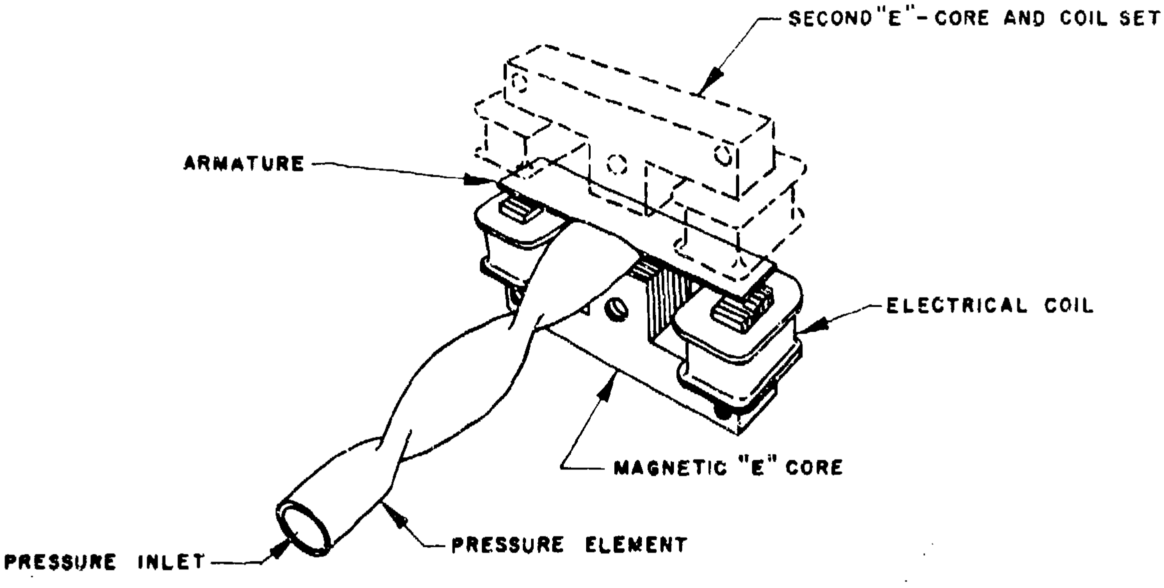

Fig. 2-38. Twisted Tube with Armature and Coils

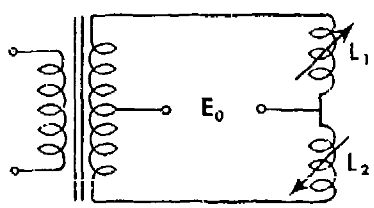

Fig. 2-39. Inductance Bridge with Two Active Arms

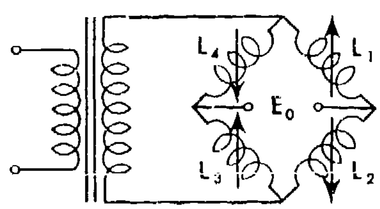

Fig. 2-40. Inductance Bridge with Four Active Arms

As illustrated by the dashed lines in Figure 2-38, the transducer may contain four inductances which are used as four active arms of the bridge circuit shown in Figure 2-40. Output voltage is approximately 20% of the input voltage for open circuit conditions.

(3) Variable Capacitance Type (Ref. 148)

Variable capacitance transducers find their greatest application in those areas requiring response to a wide range of frequencies. Capacitive transducers have good response characteristics from zero up to several thousand cycles per second.

Capacitive transducers are generally associated with the measurement of small mechanical displacements and units may be obtained for use at extremely low pressure ranges on the order of a few microns. Measurements can be made in terms of microinches if desired and can be highly accurate depending upon specific setup involving stray capacitance effects, maximum deflection, and area of capacitive plates. Their fast response makes them ideal for applications requiring precise time studies.

The capacitive transducer may be used in any electrical circuit where a change in capacity will affect the circuit. They are most commonly used in impedance bridge circuits or as the frequency determining component in an oscillator. The ruggedness of the capacitve type transducers makes them desirable in applications requiring shock, vibration, and acceleration resistant units. These retain their calibration well.

The basic mechanical configuration of a variable capacitance transducer is shown in Figure 2-41. A plate on a flexible metal diaphragm or bellows is mounted near a rigid plate and the edges electrically insulated. Pressures are applied to each side of the flexible diaphragm. The diaphragm responds to the difference between the two pressures and moves toward the side where the pressure is lower. As the distance between the movable plate and fixed plate varies, the electrical

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148 Pressure Transducing and Instrumentation Techniques, Vol. 1, Book 2, WADD Technical Report 59-743, pp. 130 - 132. AD251112

capacitance changes as a function of the applied pressure. The capacitance varies as 1/D, where D is the distance from the movable plate to the fixed plate. If changes in D are small compared with the nominal value of D, the change in capacitance is approximately a linear function of pressure.

When used as a component in an oscillator circuit, the oscillator must be of a type that can be tuned by changing capacitance. Figure 2-42 shows a simple Hartley oscillator using a variable capacitance pickoff as the frequency determining component. As the value of capacitance is changed, the oscillator frequency changes proportionally. Either static or dynamic pressures may be monitored with this type circuit. A static pressure results in a constant displacement of the diaphragm; therfore, a new steady state oscillator frequency is established. Time varying pressure changes result in time varying frequency shift of frequency modulation.

2-5 MEASUREMENT OF FLUID FLOW

a. Volumetric Flow Measurement

The three basic types of volumetric flow meters are displacement meters, velocity meters, and differential pressure meters. A great variety of each type exists, the selection being dependent upon density, viscosity, flow rate, and corrosiveness of the fluid to be measured. Meter flow range, pressure loss, monitoring technique, size, accuracy, reliability, and cost must also be considered.

(1) Displacement Meters

A displacement meter is usually in the form of a fluid pump which is run in reverse by the flowing fluid. When calibrated for a fluid of a given density and viscosity, meter reciprocation or rotation is directly proportional to the fluid flow rate, and the sum of the rotations is a measure of the fluid volume. Several of the more common displacement meters are discussed herein.

(a) Reciprocating Piston Meter

The reciprocating piston meter is essentially the reverse of a double-acting reciprocating pump. Although it is a very

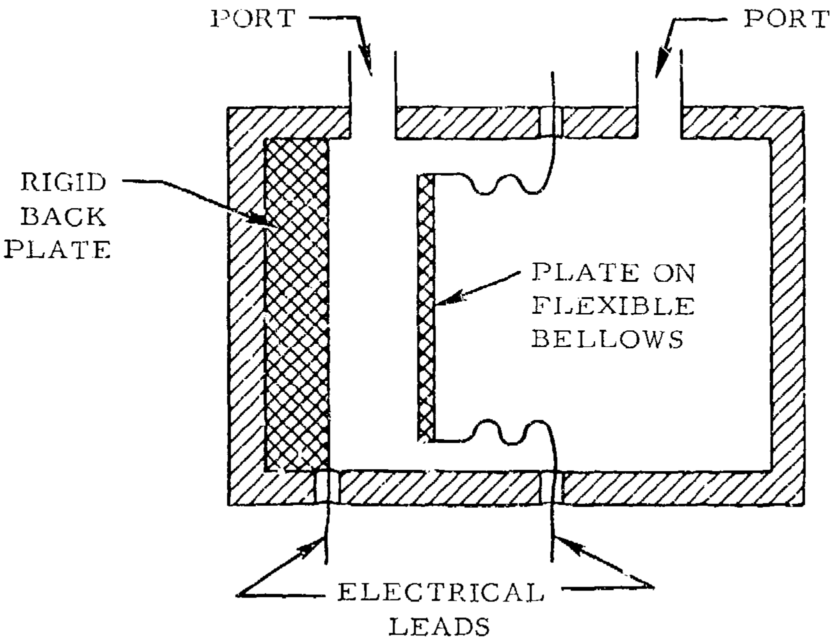

Fig. 2-41. Capacitive Transducer Configuration

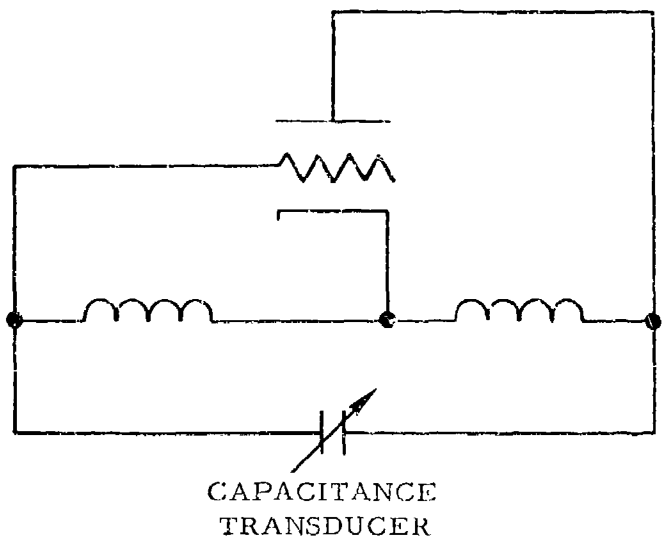

Fig. 2-42. Hartley Oscillator Using Variable Capacitance Transducer

early style meter, practically all liquids can be metered satisfactorily through suitable selection of fabrication materials. An error of 0.2% can be obtained down to virtually zero flow. To reduce wear and head loss, large pistons with short stroke are necessary with the result that the meter is inherently large in comparison with many other types.

(b) Duplex Rotor Meter (Ref. 149)

The duplex rotor meter, illustrated in Figure 2-43 has a greater flow capacity. The moving element consists of two fluted rotors. The relative position between the two rotors is controlled by two helical timing gears so that synchronized rotation is obtained. There is always a small clearance between the helical surfaces so that no metal to metal contact exists. The sequence of operations is as follows: the metered liquid enters the measuring chamber causing the rotors to move. A volume of liquid is momentarily isolated from the outlet and inlet A further movement of the rotors allows the volume of liquid to be discharged from the working chamber. Rotor motion may be monitored and recorded by electrical or mechanical means. A typical meter of this description, suitable for a three-inch pipe, has an error of approximately 0.75% from 41 gpm up to a maximum flow rate of 266 gpm and a pressure loss of about 500 psfd.

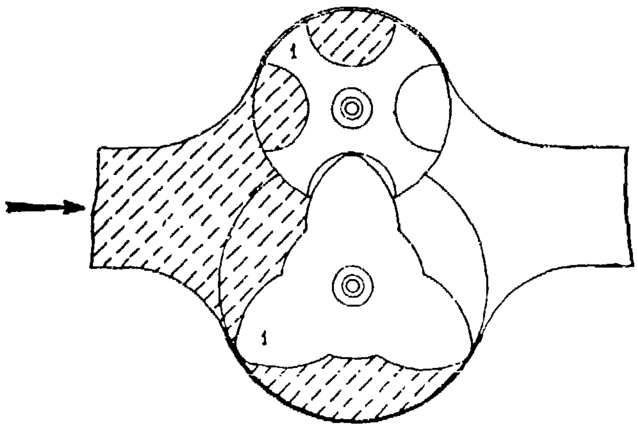

Fig. 2-43. Duplex Rotor Meter

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149 Linford, A., "Measurement of Fluid Flow," The Instrument Manual, Third Edition, London: United Trade Press, LTD, 1960, p. 122.

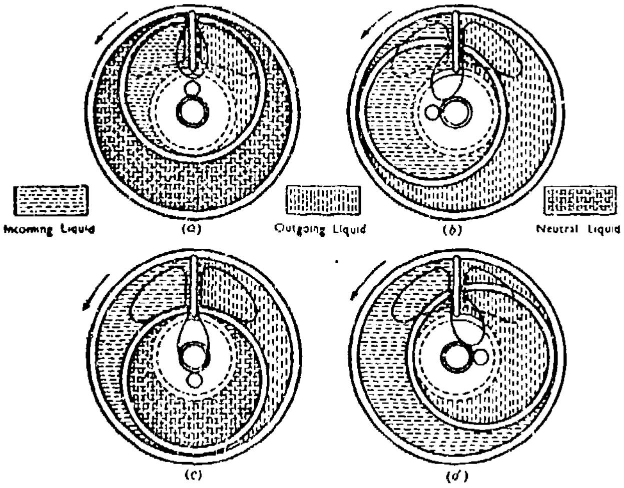

Fig. 2-44. Semi-Rotary Piston Meter

(c) Semi-Rotary Piston Meter (Ref. 150)

The semi-rotary piston meter was developed primarily for the measurement of small flows of water. However, by the careful selection of materials of construction, to withstand high temperature, any corrosive action, etc., meters of this description are now available for measuring other liquids.

The salient features of these meters are low cost and maintenance, a large flow range, interchangeability of working parts and a good commercial accuracy (error less than ±2% of actual flow) over the whole working range.

A cross-sectional diagram of this meter type is shown in Figure 2-44. The body of the meter, mounted in the pipeline, contains a cylindrical piston of somewhat smaller diameter, but of the same height as the working chamber.

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150 Ibid., pp. 122-124.

The working chamber is fitted with a radial partition projection partly across it, and with a central hub. The piston, the wall of which is split, fits over the partition, and also over the central hub. The diameters of the working chamber, of the central hub and of the piston are such that, whatever the position of the piston, line contact is obtained between its outer wall and the inner wall of the working chamber.

The liquid being metered enters the bottom of the working chamber on one side of the partition and leaves the chamber from the top on the other side of the partition, so that the piston forms a movable barrier between the inlet and outlet ports. The result is that the liquid, flowing through the working chamber, sets the piston in motion, a semi-rotary movement being obtained, the piston sliding to and fro along the fixed partition--yet always revolving round the working chamber in the same direction, although it does not rotate about its own axis. Each semi-revolution of the piston allows a volume of liquid, equal to the volume it sweeps out, to pass through the meter. The nominal sizes of these semi-rotary piston meters range from 1/2 inch to 6 inch connections. Table 2-5 gives some examples of typical meter capacities and flow ranges. Such meters are suitable for working pressures up to 21, 600 psfg.

Table 2-5. Typical Flow Ranges of Semi-Rotary Piston Flowmeter

Meter Size (inches)	Meter Starts At	Accuracy of 98% At	Rated Maximum Working Flow (64 psfd pressure loss)	Maximum Occasional Overload (1600 psfd pressure loss)
1/2	0.017 gpm	0.083 gpm	1.7 gpm	8.3 gpm
1	0.033 gpm	0.17 gpm	4.2 gpm	22. gpm
2	0.067 gpm	0.5 gpm	25. gpm	130. gpm
4	0.42 gpm	0.8 gpm	83. gpm	420. gpm
6	0.5 gpm	1.0 gpm	130. gpm	635. gpm

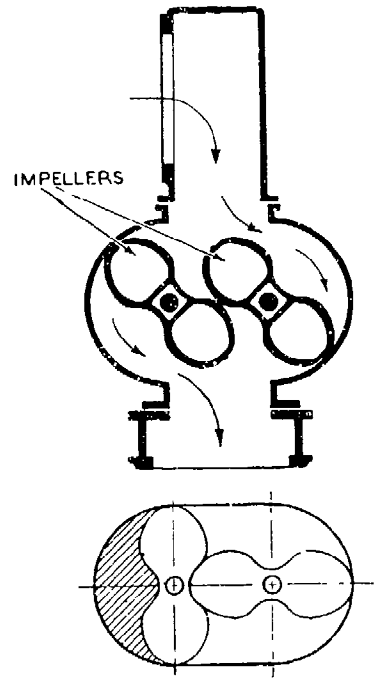

Fig. 2-45. Rotary Meter

(d) Rotary Meter (Ref. 151)

The rotary meter is one of several types of displacement gas meters. As shown in Figure 2-45, it consists of a working chamber containing two impellers, each mounted on a shaft. The gas enters the working chamber from the top and, in exerting a pressure on these impellers, causes them to rotate. The relative position of the two impellers is determined by gears fitted on their respective shafts, and it will be seen that, owing to their shape, they are always in contact with each other. Each complete revolution of the impeller necessitates their passing through the vertical position twice, and each time a pocket of gas (shown hatched in Figure 2-45) is trapped. Hence, the volume of gas passed for each revolution of the impellers is four times the hatched portion multiplied by the length of the impellers.

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151 Ibid., pp. 124-125.

The working range of these meters is from 1 to 10 times the minimum accurately measurable flow and overload of from 50% to 100% can be allowed. Capacities range from 333 cfm (6" gear diameter by 18" impeller length) to 21, 530 cfm (32" gear diameter by 96" impeller length), the head loss being approximately 2. 5 psfd and the working pressure 1440 psfg. These meters have been designed for working pressures up to 43, 200 psfg.

(2) Velocity Meters

Meters of this type obtain a measure of the velocity of the flow; the volumetric flow is inferred as being equal to the velocity multiplied by the cross sectional area of the flow. The moving element is usually a helix, fan, or turbine rotor. Minimum flow rates which can be measured with acceptable accuracy are generally higher than those for displacement meters, depending on the frictional and in inertial characteristics of the particular device. Lower total pressure loss, lower cost, and the ability to handle a variety of corrosive fluids containing suspended matter are some advantages. It is important, however, that a velocity meter be calibrated for the specific fluid and conditions encountered in use. Velocity meters are commercially available from numerous manufacturers. Two modern types are discussed herein.

(a) Turbine Flowmeter (Ref. 152)

The "Pottermeter," illustrated in Figure 2-46 consists of a housing with end fittings to match those of the piping in which the element is to be installed. A hydraulically, self-positioning rotor is suspended within the housing. A permanent magnet is sealed inside the rotor of the standard frequency Pottermeter. High-frequency meters utilize a reluctance type magnetic pick-up with a permanent magnet built into an externally-mounted coil.

As the fluid flows through the element, the rotor spins at a speed determined by the fluid velocity and the angle of the rotor blades, inducing an ac voltage in the pick-up coil mounted externally to the housing. In standard frequency meters, the frequency of this voltage is a function of the rotor speed and the number of magnetic poles. High-frequency meters produce a frequency up to 10 times greater for use in transient flow studies, digital flow rate indication, and telemetering.

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152 "Engineered by Potter," Potter Aeronautical Corporation, Union, New Jersey.

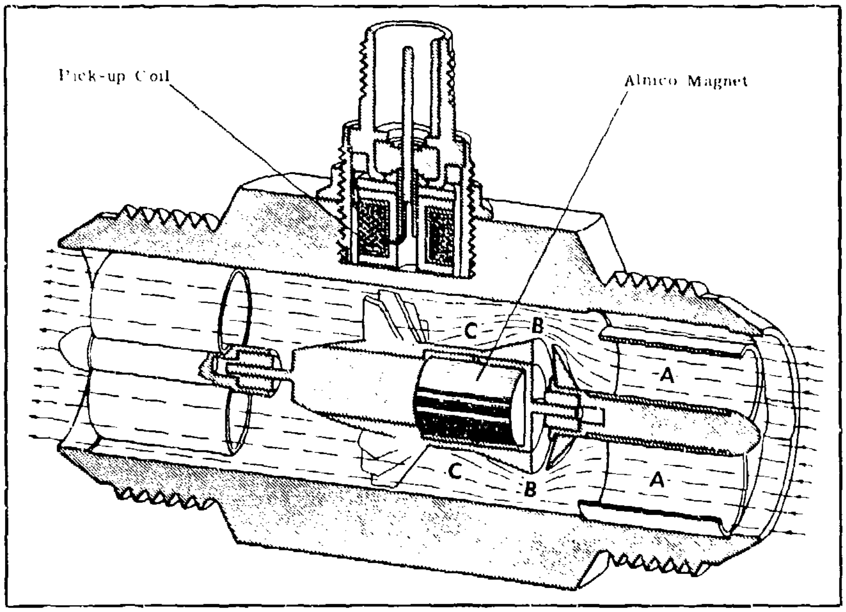

Fig. 2-46. Turbine Flowmeter

The design of the rotor and its supporting members is such that fluid flow through the element establishes upstream thrust components which exceed the downstream drag factor, so that the rotor spins freely without thrust friction midway between its upstream and downstream supports.

At point A (See Figure 2-46), the upstream end of the unit, fluid flow is assumed to be at line velocity and pressure. This flow encounters a restricting cone, held rigidly in place, which causes an increase in velocity with a corresponding decrease in pressure in the area between the rotor and the stationary cone at Point B. The restricting cone attached to the upstream support is slightly smaller in diameter than the body of the rotor, and therefore absorbs the impact of the downstream flow velocity so that only a limited amount is permitted to be impressed upon the rotor. Since the rotor itself is shaped like a cone with the base upstream, there is a decrease in fluid velocity along the body of the rotor with a corresponding pressure recovery at Point C, which tends to force the rotor upstream into the low pressure area behind the stationary cone. There is actually an excess of upstream thrust so that the rotor moves up-stream to a point where the flow past the smaller, fixed, upstream cone

begins to impinge on the forward edge of the rotor body, limiting the amount of upstream movement.

When hydraulically centered in this position, the rotor spins without slippage or thrust friction. The error is approximately ±0.5% of the actual flow.

The meter is inherently linear over most of its range of operation. Some non-linearity will be encountered when operating at minimum flow rates, at which the fluid velocity is not high enough to produce sufficient upstream thrust to overcome the drag on the rotor. Even at these low flow rates, the element has a high degree of repeatability.

The meter can be installed in any position, horizontally or vertically, with the flow either upward or downward so long as the flow is in the direction indicated on the housing. However, linearity over the widest possible range of operation will be obtained when the unit is mounted within 15° of the horizontal. Because the rotor spins freely, it responds rapidly to flow changes and will fully indicate a transient change within the time required for the rotor to make one complete revolution.

Table 2-6 lists representative sizes, capacities, and flow ranges; however, many other sizes are available.

Table 2-6. Typical Ranges of Turbine Flowmeters

Meter Size (Inches)	Repeatable Performance Starts At	Linear Performance Starts At	Rated Max. Working Flow (1728 psfd press. loss)
1/8	0.08 gpm	0.17 gpm	1.4 gpm
1/2	1.2 gpm	2.0 gpm	25.0 gpm
1	3.7 gpm	6.0 gpm	94.0 gpm
6	180.0 gpm	350.0 gpm	6400.0 gpm
12	650.0 gpm	1200.0 gpm	26,000.0 gpm

(b) Vortex-Velocity Flowmeter

The Vortex-Velocity flowmeter is illustrated in Figure 2-47 and its principle of operation is shown in Figure 2-48. (Rotron Controls Corporation, Woodstock, New York.)

This meter type has a continuous flow range of 10 to 1 regardless of meter size. It will measure liquids, atmospheric air, or compressed gases. Temperature limits may range from 32°F to 200°F.

The Vortex-Velocity flowmeter consists essentially of a piece of straight pipe with an offset cylindrical chamber. When a fluid flows through the pipe, an eddy or vortex forms in the chamber. The rotation of the vortex is inherently proportional to the main flow in the pipe. A rotor mounted in this vortex senses the vortex promptly and maintains its stability. The rotor merely rides with the vortex as a means of counting its revolutions. A magnetic coupling between the rotor shaft and the register eliminates the need for packing glands.

Counting the number of revolutions, or speed of the vortex, produces an accurate volume total or flow rate indication of mass flow at line conditions. The meters have an error of 0.5% and a flow range of 20 to 200 gpm for liquids, and 10 to 100 cfm for gas.

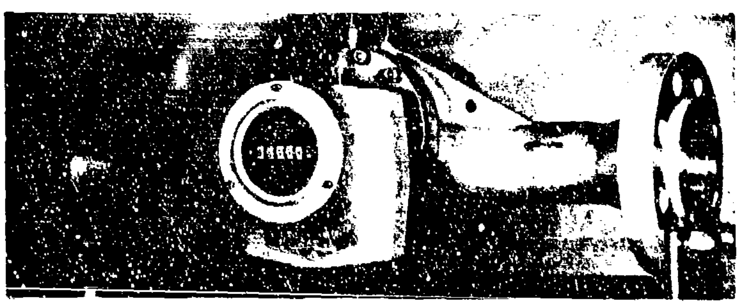

Fig. 2-47. Vortex-Velocity Flowmeter

(3) Differential Pressure Meters (Ref. 153)

Differential pressure meters consist either of a probe or a constriction in a conduit. There is no limit to the size of these

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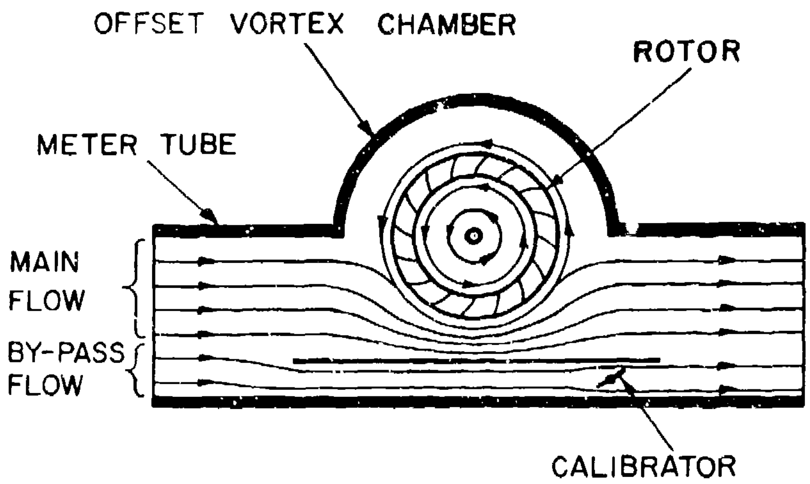
153 Linford, A., op. cit., pp. 131-138.



Main flow produces vortex in offset chamber.

Vortex motion is sustained by engagement of portion of vortex periphery and adjacent streamline of crowded main flow. Relation is "pulley on a belt."

Rotor turns with vortex which has a regulated diameter larger than that of rotor. Main flow does not engage rotor blades.

Shunt flow, not shown, supplies fluid to center of vortex. Resulting radially outward flow component provides necessary relative motion to avoid tangential slip between rotor and vortex.

By-pass flow is regulated by calibrator to change relation between rotor revolutions and total flow. Thus, meter factor can be adjusted to unity.

Three parallel flows have common pressure drop and operate in turbulent range. Hence, measured flow is constant proportion of total flow.

Fig. 2-48. Principle of Vortex Velocity Meter

meters, and they have the ability to handle corrosive fluids containing large amounts of suspended matter.

A flowing fluid has a total (ram or stagnation) pressure which is the sum of its static and dynamic pressures. These terms are often referred to as total, static, and dynamic (velocity) head, respectively, when the pressure is expressed in feet or inches of the working fluid.

if

P_t = total pressure (lb/ft^2)

P_s = static pressure (lb/ft^2)

P_d = dynamic pressure (lb/ft^2)

ρ = fluid mass density ($lb\text{-}sec^2/ft^4$)

V = fluid velocity (ft/sec)

$$P_t = P_s + P_d \qquad (2\text{-}13)$$

where

$$P_d = (1/2)\,\rho\, V^2$$

therefore

$$P_t = P_s + (1/2)\,\rho\, V^2 \qquad (2\text{-}14)$$

thus

$$V^2 = 2(P_t - P_s)/\rho \qquad (2\text{-}15)$$

Fluid flow rate is directly proportional to fluid velocity and therefore to the square root of the differential pressure, as shown by equation (2-15).

(a) Pitot Tube

The Pitot tube may be used to measure the differential pressure for the determination of velocity or volumetric flow.

Two configurations are shown in Figure 2-49.

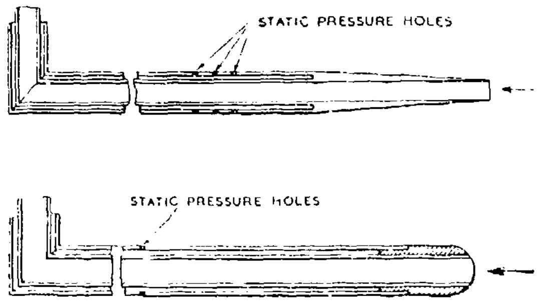


Fig. 2-49. Pitot Tubes

The Pitot tube is inserted into the stream of fluid. Fluid is brought to rest in the center tube giving total pressure. Static pressure is obtained by the concentric outer tube. A differential pressure gauge is used to measure $P_t - P_s$ which is proportional to the velocity of the flow at the point in the stream where the Pitot tube is located. To ascertain the total flow through a conduit, it is necessary to relate this velocity to the mean velocity of the flow. It is usual to locate a Pitot tube at the center of the conduit where the velocity distribution curve is flattest. The ratio of mean velocity to center velocity is a function of Reynolds number.

(b) Venturi Tube

Of the various forms of volumetric flow meters, those which employ a detecting element operating on the following differential pressure principle have the widest application. The operation of the detecting element is based upon increasing flow velocity (dynamic pressure) causing decreasing static pressure. Thus, if total pressure is assumed constant between sections 1-1 and 2-2 (Figure 2-50), equation (2-14) becomes

$$P_{s_2} + (1/2)\rho_2 V_2^{\,2} = P_{s_1} + (1/2)\rho_1 V_1^{\,2} \qquad (2\text{-}16)$$

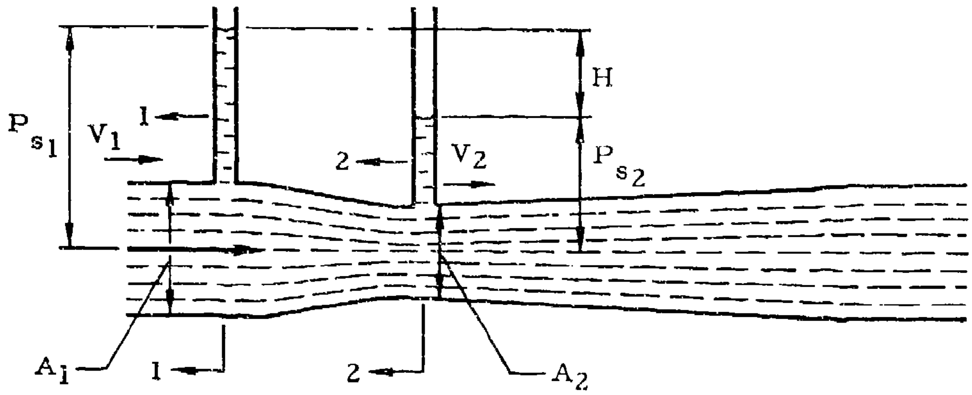


Fig. 2-50. Venturi Tube

When dealing with compressible fluids, the density at section 1-1 is not the same as the density at section 2-2 due to the change of pressure. However, in a correctly designed differential pressure producing device, the error involved is negligible.

From (2-16), it may be seen that

$$V_2^{\,2} - V_1^{\,2} = \frac{2(P_{s_1} - P_{s_2})}{\rho} \tag{2-17}$$

since

$$A_1 V_1 = A_2 V_2 \tag{2-18}$$

by substitution

$$V_2 = \sqrt{2\,(P_{s_1} - P_{s_2}) / \rho\,(1 - A_2^{\,2}/A_1^{\,2})} \tag{2-19}$$

Thus, the square root of the static pressure difference is a measure of the volumetric flow rate.

In addition to the Venturi tube, there are other devices available for metering fluid by this principle. The criterion for such a meter is the ability to produce a high differential pressure with a low total pressure loss. Typical devices of this type are the orifice and Dall Tube.

(c) Orifice Meter

The orifice meter shown in Figure 2-51 is a thin metal plate with a central hole. Pressure taps are provided on each side of the orifice plate. Being simple and inexpensive, the orifice

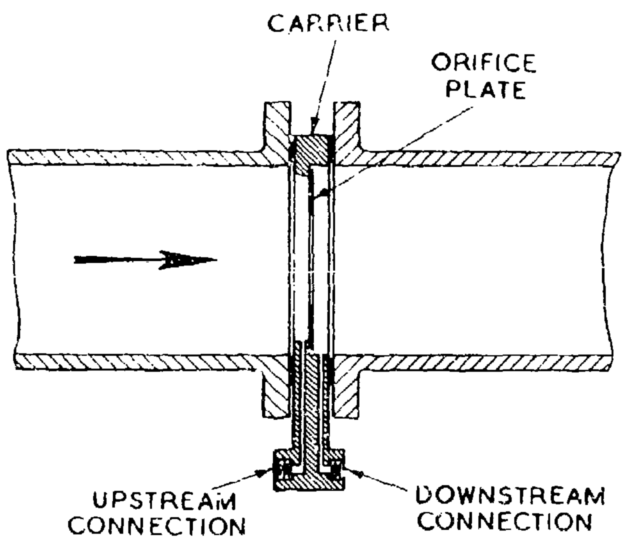


Fig. 2-51. Orifice Meter

generates a large differential pressure, but has the disadvantage of a large total pressure loss, primarily due to downstream turbulence

(d) Dall Tube

The Dall tube, illustrated in Figure 2-52, combines the high differential of an orifice with the low loss of a Venturi.

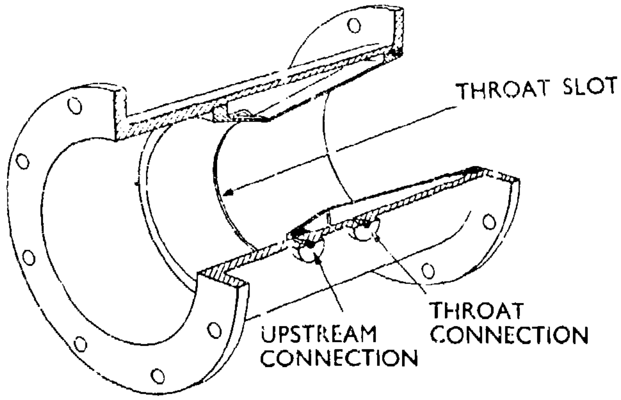


Fig. 2-52. Dall Tube

It is shorter (1-1/2 to 2 pipe diameters) and has less pressure loss than the Venturi.

(e) Comparisons

Table 2-7 presents a comparison of the efficiencies of several differential pressure meters.

Table 2-7. Comparison of Differential Pressure Meters

Type of Meter	Pressure loss in per cent of differential produced for various throat dia/inlet dia. ratios.			
	0.2	0.4	0.6	0.8
Orifice	95%	82%	62%	40%
Nozzle	92%	74%	50%	--
Short Venturi	30%	16%	10%	10%
Long Venturi	15%	11%	10%	10%
Dall Tube	--	9%	4%	3%

b. Mass Flow Measurement (Ref. 154)

Devices to measure mass flow or weight flow have aroused great interest during the past few years. This interest stems from the need in industrial process control and military fields for more accurate and faster ways of metering fluid than is possible with conventional inferential-type flowmeters. Inasmuch as missile thrust is measured in terms of the weight of propellant delivered, mass flow or weight flow information is of infinitely greater value and importance than the volumetric flow rate.

Because of their simpler construction, conventional inferential meters such as area or head meters have been used extensively in the past. To obtain mass rate of flow information from these meters, the reading must be corrected for related fluid properties such as density and viscosity as well as such environmental conditions as temperature and pressure. With present highly developed computational techniques, it is theoretically possible to correct these quantities automatically, and any inferential type meter can be made to measure mass rate of flow by correcting, with suitable transducers, the effects of density, viscosity, pressure, velocity, etc. Unfortunately, since these quantities are often interrelated in a rather complicated fashion, a high degree of accuracy over a wide flow range cannot be obtained easily. The situation is complicated further when the fluid is nonhomogeneous (i. e., compressible fluid, multiphased fluid such as mists, slurries, foams, emulsions) and when the flow is not steady (i. e., pulsating flow).

A true mass flowmeter, on the other hand, is one that can produce a signal which corresponds to the mass rate flow directly and is substantially independent of various fluid properties and environmental conditions. Since modern power plants and missiles are frequently subject to appreciable transient variations in fluid properties, the relative independence of mass flowmeters on these variable conditions assures better accuracy over a wider range of operation than compensated inferential meters.

The basic types of flowmeters are listed in Table 2-8 along with several of the most widely used sub-classifications.

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154 Miesse, C. C., Study of Mass Flowmeters, Armour Research Foundation, Final Report (ARF Project D173), July, 1959.

Table 2-8. Classification of Mass Flowmeters

Classification	Sub-Classification
Conventional Inferential Meters with Automatic Compensation	Head or area meters with density and possible viscosity compensation. Velocity meter with density compensation.
Transverse-Momentum Flowmeter	Radial Flow Type Axial Flow Type Gyroscopic Type
Forced Circulation Flowmeter Flow Acceleration Flowmeter	Constant displacement pump Magnus effect

(1) Transverse Momentum Flowmeter

Utilization of the momentum force of the fluid stream to measure flow rate is a relatively simple matter. Unfortunately, the force produced is not merely a function of the mass rate of flow, but also a function of density of the fluid. This difficulty can be overcome by superimposing a known velocity in a direction perpendicular to that of the stream. The force required to accelerate or retard the fluid stream is equal to the rate of change of momentum in the transverse direction, which in turn is proportional to the mass rate of flow. Mass flow signals obtained by this method are substantially independent of fluid properties such as viscosity, density, and homogeneity and environmental conditions such as temperature, flow patterns, etc. The linear relationship between the mass rate of flow and the force output is also a very desirable feature. The three different arrangements which have been developed are known as the radial flow type, axial flow type, and gyroscopic type.

(a) Radial Flow Type

The radial flowmeter, also known as the Li mass rate meter, is shown in Figure 2-53. Its flow sensing element is in the form of a tube or a turbine impeller. The fluid flows in the radial direction relative to the sensing element, and each fluid particle traces a spiral-shaped path in space. The sensing element is forced to rotate at a constant angular velocity, and the torque required to rotate the sensing element is a linear function of the mass rate flow.

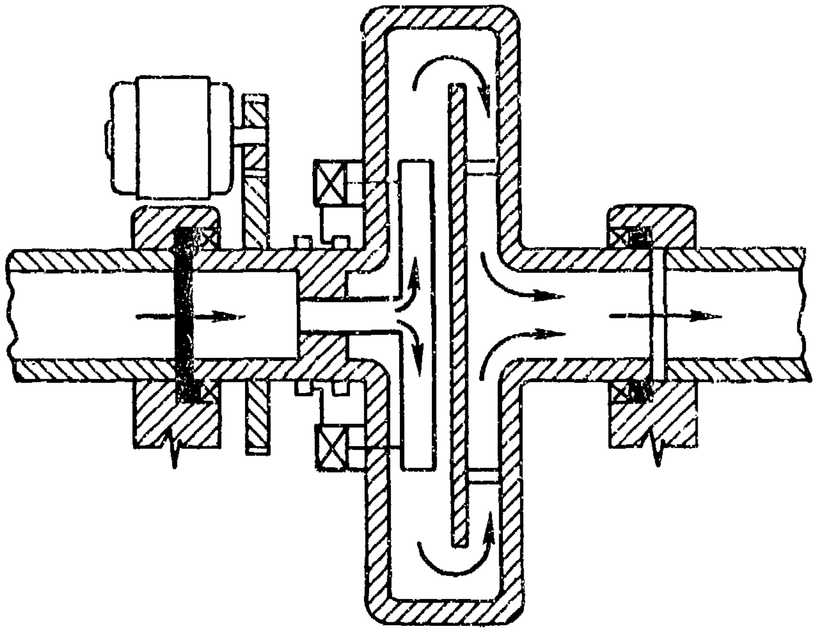

Fig. 2-53. Schematic Diagram of Li Mass-Rate Flowmeter

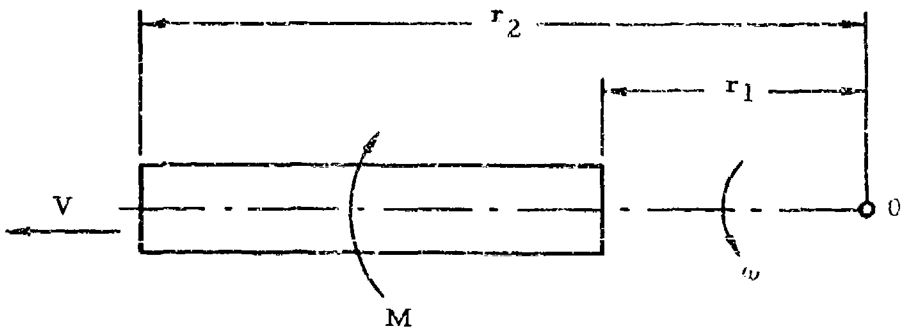

Fig. 2-54. Description of Operation of Li Radial Flowmeter

The operation can be described most readily by referring to the special illustration of Figure 2-54 where the fluid is assumed to flow uniformly through a straight tube, the motion of each partical being parallel to that of the others. The tube is assumed to be rotated at a constant angular velocity ω about the axis 0 intersecting the axis of the tube at right angles. The Coriolis acceleration, which is then uniform everywhere in the fluid, is given by the equation:

$$a = 2V\omega \qquad (2\text{-}20)$$

where

V = fluid velocity relative to the tube.

From this, it can be shown that the moment about 0 due to the Coriolis force is given by

$$M = \omega\,(r_2^{\,2} - r_1^{\,2})\,W \qquad (2\text{-}21)$$

Hence, the moment or torque is a linear function of the mass rate of flow, W.

It can also be shown that the shape of the flow sensing element is of no importance, nor are the properties of the fluid or the nature of the flow pattern within the vessel. The only significant requirement is that the entrance and exit velocities relative to the vessel be radial. If this condition is not fulfilled, an additional moment will be produced by the tangential components of the velocities as in the case of a radial flow turbine, and the linear relationships for force and moment will no longer apply.

Practical arrangement embodying this principle is shown in Figure 2-55. The flow sensing element in this case resembles the impeller of a centrifugal pump. It is enclosed in a housing that also resembles a pump housing except that it rotates with the impeller and is mechanically connected to it by an elastic member whose distortion serves to measure the moment exerted on the impeller by the fluid, and therefore, the mass rate flow. The whole assembly is rotated at a constant rate by an external motor, and connections between the incoming and outgoing fluid lines are made through any suitable type of rotary seal. The impeller is provided with a sufficient number of radial vanes to ensure

that the flow is substantially radial (See Figure 2-56), so that the output, taken from a device that measures torsional deflection with respect to the housing, will be an accurate measure of the mass flow rate.

It is interesting to note that in the arrangement of Figure 2-55, the torque required to drive the flow sensing element is recovered in the guide vanes in the housing, with the result that the only torque which the driving motor must supply is that necessary to overcome bearing and seal system friction and windage. It should also be noted that the signal output is independent of this frictional torque.

Such a device as depicted in Figure 2-55, unlike some other types of flowmeters, can be used bidirectionally; i.e., if the flow reverses, the torque produced also will reverse. Similarly, the torque can be reversed by reversing the drive motor, or the scale factor can be changed by changing the motor speed.

Basically, the only source of error in this flowmeter is the possible tangential component of the relative velocity at either the inlet or the outlet of the impeller. If the relative velocity can be held truly radial at both inlet and outlet of the impeller by a suitable arrangement of vanes, the meter can be very accurate. This is true even if the fluid is compressible or nonhomogeneous.

The flowmeter is also very useful for pulsating type flow measurement, since the basic momentum equation is valid even when the flow is not steady. As the flowmeter is basically linear, the average output signal is a linear function of the average flow rate.

(b) Axial Flow Type

In the axial flow type, a sensing element having a series of parallel flow passages is made to rotate about an axis parallel to the flow passages. The fluid flows in an axial direction relative to the sensing element, and each fluid particle traces a helical-shaped path in space. The torque required to drive the sensing element is also a linear function of the mass rate flow.

One flowmeter of the axial flow type is the General Electric Mass Flowmeter which consists of two similar cylinders placed end-to-end so that the two axes coincide (See Figure 2-57). The

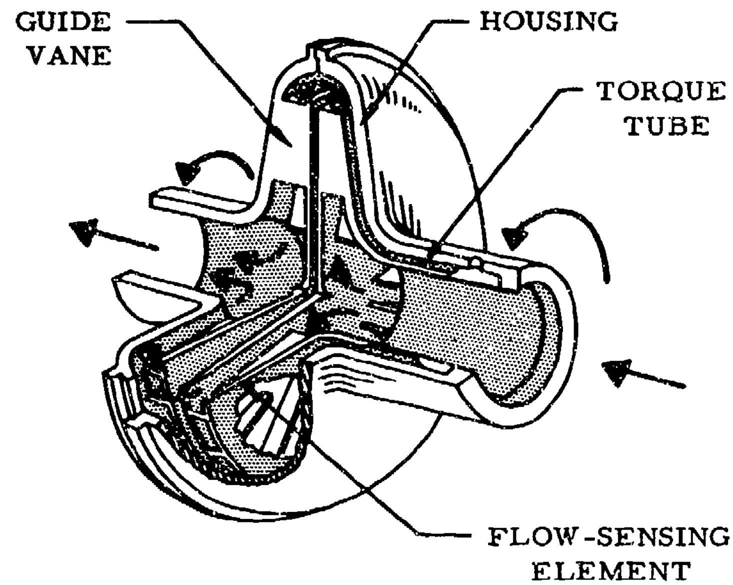

Fig. 2-55. Schematic Diagram of Coriolis Type Mass Flowmeter (Control Engineering Corporation)

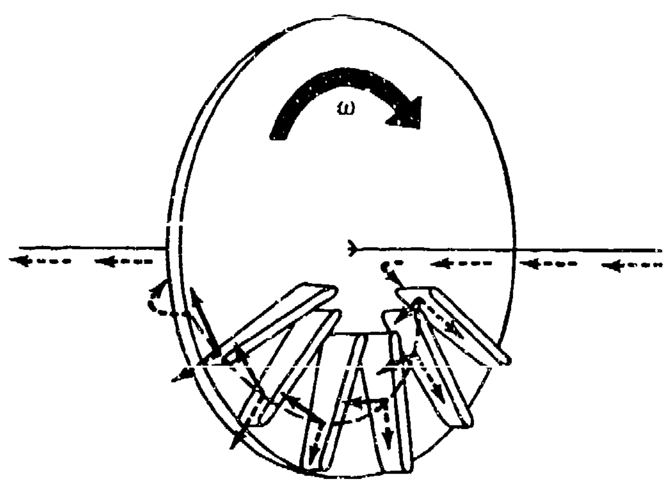

Fig. 2-56. Particle Path Through Flow Sensing Element

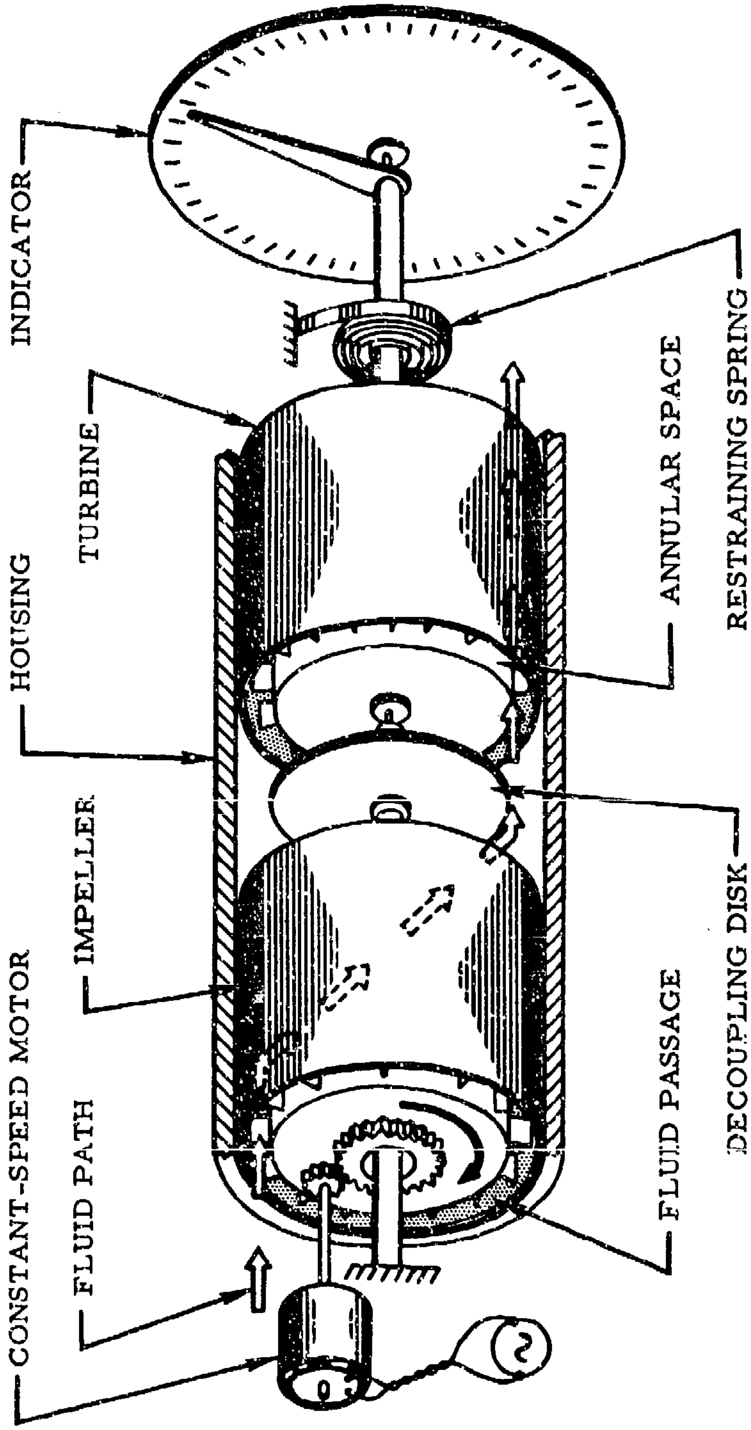

Fig. 2-57. Pictorial Diagram of General Electric Mass Flowmeter

instrument housing closely fits the outer diameter of the cylinders. Around the periphery of the cylinders are located a number of passages, the axes of which are parallel to the axis of the cylinder. Fluid moving through the pipeline enters the passages in the first cylinder, proceeds through the passages in the second cylinder, and continues along the pipeline. By driving the upstream cylinder, termed the impeller, at a constant angular velocity about its axis, the fluid is given a constant velocity at right angles to the fluid flow. This angular velocity constitutes a change in momentum of the fluid. The second cylinder, termed the turbine, is designed to remove all the angular momentum from the fluid. In so doing, a torque is exerted on it in accordance with Newton's second law of motion. This torque deflects a spring which restrains the turbine. The angular deflection of the turbine is a measure of the mass rate flow.

The equation relating the mass rate flow and the torque output can be derived by using the law of angular momentum. The rate of change of angular momentum of the fluid leaving the impeller is $W \omega K^2$, where K is the average radius of gyration, the value of which depends on density distribution as well as on velocity distribution. In this case, $r_o > K > r_1$, where r_o and r_1 are the outside and inside diameters of the openings, respectively.

If the turbine is placed very close to the impeller, the assumption can be made that all the angular momentum generated by the impeller is absorbed by the turbine. By the angular momentum principle, the torque produced on the turbine is equal to the rate of flow of angular momentum. Thus, if the angular velocity ω can be maintained a constant, and if K can be assumed a constant, the torque acting on the turbine will be a linear function of the mass rate flow. This torque can be measured conveniently by the use of a mechanical spring and a dial, as shown in Figure 2-57 or converted to an electrical signal by a suitable angular displacement transducer.

In operation, there is some coupling effect between the impeller and the turbine even when the flow rate is equal to zero. This coupling effect is due partly to the viscous drag of the fluid and due partly to radial flow caused by centrifugal force. This latter action is very similar to the fluid coupling in an automobile. It is found that by placing a plate, termed a decoupling disc, between impeller and the turbine, the coupling effect can be reduced appreciably. However, the plate covers only the central portion of the conduit; consequently, the viscous drag acting on the

outer periphery of the turbine still exists. The coupling effect is probably one possible source of error, especially when the viscosity is high and when the temperature range is large. Another likely source of error is the possible variation of K due to non-homogeneity of the fluid. When the fluid is compressible, the density at the outer periphery undoubtedly will be higher because of centrifugal force. When liquid flow is measured, any air or vapor that is trapped in the liquid will tend to collect at the inner side of the passages. Both conditions can cause a higher value of K. Variation of velocity distribution in the passages can also cause variation in K.

This type of flowmeter is simple compared with some other methods of obtaining true mass flow, but becomes inaccurate at low flow rates, where extraneous torques exert their influence. Furthermore, it can measure flow in only one direction, and cannot follow rapid changes in flow.

The Avien flowmeter shown in Figure 2-58 also operates on the axial flow principle. It contains two impellers driven in opposite directions at a speed proportional to line frequency. This arrangement permits measurement in either direction of flow. A sensing wheel, restrained by an electromechanical torquer rather than a mechanical spring, removes the angular momentum from the fluid. The torque motor providing the restraint receives an amplified potentiometer signal which is proportional to the angular position of the sensing wheel, and thus proportional to the mass flow rate times the angular velocity of the impeller.

To make the flowmeter output dependent only on the mass flow rate requires a constant angular velocity. But the angular velocity, being proportional to line frequency, varies with changes in line frequency. Such variations can be compensated by feeding the transducer output signal into a line frequency correcting network and using the resulting output to drive a servo amplifier-recorder. When the line frequency varies from nominal, the attenuation of the correcting network changes in the proper direction to compensate for the change in impeller angular velocity.

A twin-turbine mass flowmeter (Ref. 155) is shown in Figure 2-59. It incorporates a rotor having two sets of turbine blades with different blade angles, coupled by a spring and capable of relative angular motion with respect to each other. As a result of the blade

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155 "Engineered by Potter," Potter Aeronautical Corporation, Union, New Jersey.

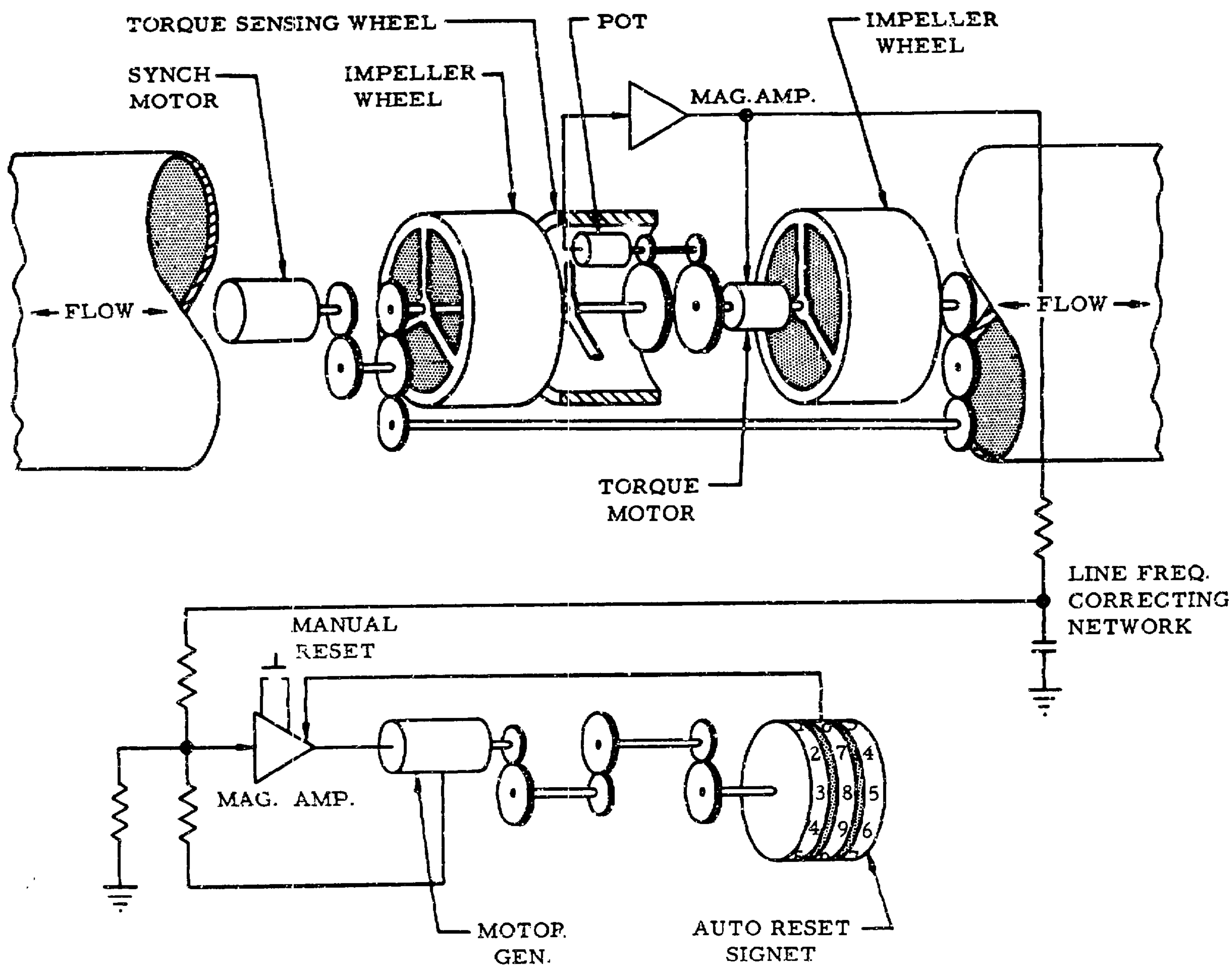

Fig. 2-58. Avien Flowmeter

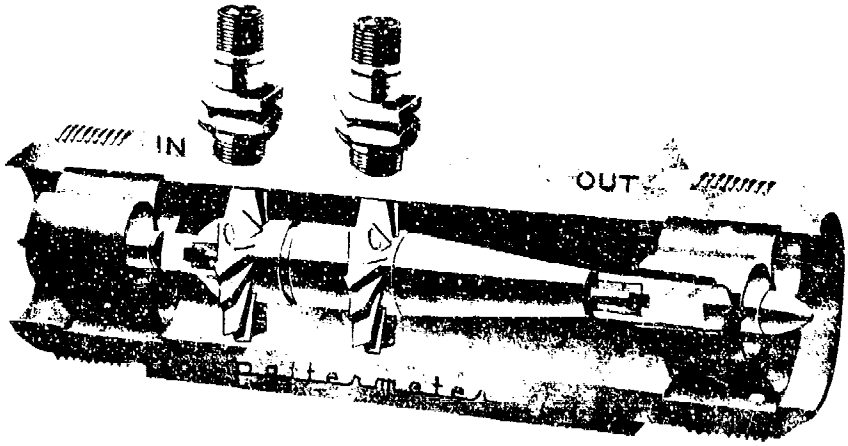

Fig. 2-59. Twin Turbine Mass Flowmeter

angle difference, the two sets of blades tend to rotate at different speeds, but cannot because of the spring coupling. They thus take an angular displacement with respect to each other, the magnitude of which is proportional to the flow momentum. However, the rotor assembly, considered as a unit, functions as a volumetric turbine meter rotating at a speed proportional to the average fluid velocity.

In terms of the equilibrium period P between the two-rotor system,

$$\theta = 2\pi t/P = 2\pi t f \qquad (2\text{-}22)$$

where t is the time for the two-rotor system to sweep the deflection angle, f is the frequency of the system, and θ is the phase angle between turbines. On the other hand,

$$\theta = T k \qquad (2\text{-}23)$$

where T is the torque and k is the spring constant for the coupling spring. From Equations (2-22) and (2-23),

$$t = \left(\frac{k}{2\pi}\right)\frac{T}{f} \qquad (2\text{-}24)$$

where the term in parentheses is constant.

From hydrodynamical considerations

$$T = Fr = \rho A V^2 r \tag{2-25}$$

where F is the hydrodynamic force and r is the effective radius.

Hence

$$t = \left(\frac{k r}{2\pi} \right) = \frac{\rho A V^2}{f} \tag{2-26}$$

Since

$$f = \frac{V}{c'} \tag{2-27}$$

$$t = \left(\frac{c' k r}{2\pi} \right) \rho A V \tag{2-28}$$

Thus by measuring the elapsed time taken for the phase angle displacement to traverse a reference point, a direct measure of mass flow rate is effected.

The signal output is generated by bits of magnetic material (which are part of each turbine assembly) as they move past the coil. Most conventional time interval measuring instruments can be used to record its output.

(c) Gyroscopic Type

In the gyroscopic type of meter, the transducer is in the form of a circular or square loop that is made to rotate about an axis in the plane of the loop. No net torque is required to rotate the sensing element, but a torque acting in a direction perpendicular to both the plane of the loop and its axis of rotation is produced. This torque is also a linear function of the mass rate of flow.

The gyroscopic meter derives the name from the similarity of its operation with a mechanical gyroscope. Figure 2-60 shows that the meter consists of a fluid conduit bent in the form of a circle (or a square) and driven at an angular velocity ω about the A-axis. The

whirling fluid produces a flywheel effect similar to that of a mechanical gyroscope rotating about the C-axis. Similar to a mechanical gyroscope,

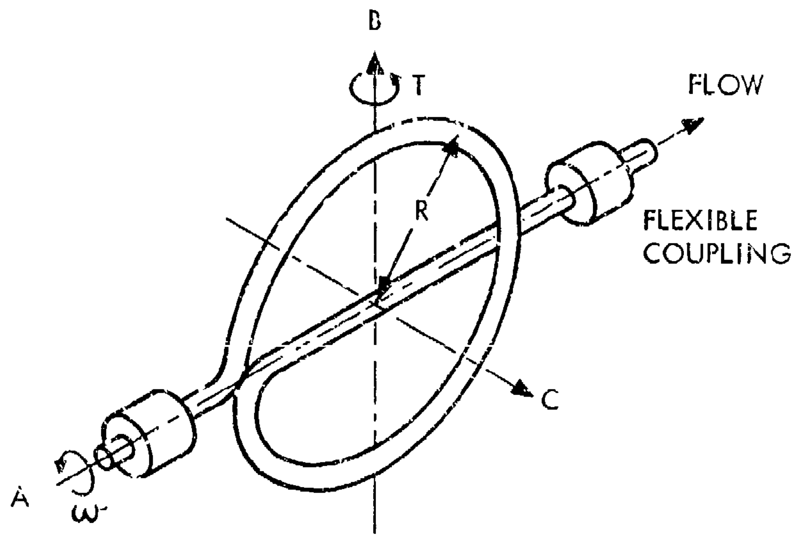

Fig. 2-60. Gyroscopic Mass Flowmeter

a moment T acting about an axis perpendicular to both A and C is produced. This moment can be shown to be a function of the mass flow rate through the flowmeter.

To simplify the discussion, the assumptions are made that the fluid is incompressible and homogeneous and that the flow is laminar and evenly distributed across the cross-section of the conduit.

The moment produced about the B-axis, can be found by the well known gyroscopic equation:

$$T = I\ \Omega\ \omega \tag{2-29}$$

$$T = W\ 2\pi\ r^2\ \omega \tag{2-30}$$

where

I = polar moment of inertia of fluid in conduit about C-axis

Ω = average angular velocity of fluid in conduit

ω = angular velocity about the A-axis

r = average radius of conduit

W = mass rate flow

The above equation shows that under assumed conditions, T is a linear function of the mass rate flow and is independent of the density and viscosity of the fluid.

(2) Thermal Flowmeters

Mass rate of flow meters have been developed which are based on thermal concepts. The fundamental idea is to subject a heat sensitive element (thermocouple) to the fluid flow and measure the cooling which takes place. The instrument is a mass flowmeter if $\sqrt{KS\rho}$ is a constant, where K is the thermal conductivity, S is the specific heat at constant volume, and ρ is the fluid density. For many fluids, this term is constant over wide ranges of pressure and temperature allowing the instrument to be calibrated directly in terms of pounds of gas per hour passing the sensing element.

The Trans-Sonics Type 1994 Mass Flow Transducer shown in Figure 2-61 consists of two platinum temperature probes extending from a case (Ref. 156). The platinum resistance windings, located at the ends of the probes and protected by stainless-steel cages, are the active elements in opposite arms of a dc resistance bridge.

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156 "Mass Flow Transducer," Trans-Sonics General Catalog and Transducer Handbook, Special Product Note No. 1994.

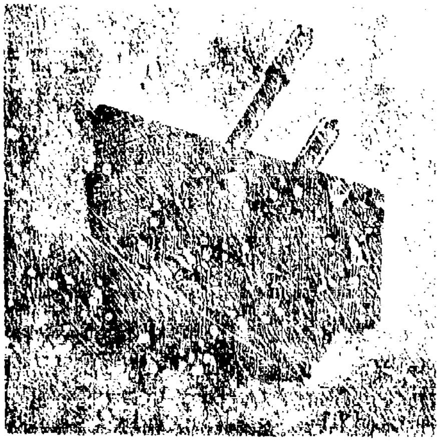

Fig. 2-61. Trans-Sonics Mass Flowmeter

The platinum resistance windings make the basic temperature measurements from which the total mass flow in the duct is determined. When the transducer is installed, the longer probe places a winding at the centerline of the duct. This resistance is heated by a relatively high steady-state current and, in accordance with laws of heat transfer, makes the fundamental density-velocity measurement as it is cooled by the mass flow in the duct.

The other platinum resistance winding on the shorter probe is unheated and is therefore not significantly affected by mass flow. Its purpose is to compensate for changes in the gas temperature in the duct by introducing a voltage which cancels out any bridge unbalance caused by the gas temperature's effect on the longer sensing probe.

Input voltage is regulated by zener diodes, thus maintaining a constant input power to the heated probe and restricting heat transfer rate to a dependence of mass flow rate only.

The mass flow rate output signal is typically calibrated for a mass flow range from 20 - 180 lbs/min., although other range calibrations are available without modification. When displayed on a dc microammeter, the instrument error is 3% of full-scale range or 10% of the actual mass flow, whichever is greater.

(3) Summary

Specifications, operating principles and advantages of several true mass flowmeters are summarized in Table 2-9.

2-6 MEASUREMENT OF ROTARY SPEED

a. Introduction (Ref. 157)

The systems that are presently used for measurement of shaft rotary speed in aircraft engine auxiliaries are ac induction tachometers, dc tachometers, and drag-cup or drag-torque tachometers. These conventional tachometers systems are adequate for many applications and have many desirable features, including long development and service histories, and a minimum of auxiliary circuitry required. However, in planning advanced weapon systems, there is a need for improved techniques for measurement of shaft speed, particularly in regard to ability to operate in severe ranges of temperature and nuclear radiation environment, operation over wider speed ranges, and with greater accuracy.

A complete tachometer system includes a rotary speed transducer, auxiliary circuits, and an output device. The transducer portion of a tachometer system consists of an element or elements mounted on, attached to, or embodied in, the shaft which is to rotate, and a fixed element or elements in proximity to the rotating elements. The functions of the transducer elements are to effect an exchange of energy or to modify an exchange of energy between the fixed and moving elements which is functionally related, in some manner, to shaft angular velocity, and to convert the speed-modified energy to an eletrical signal. It is clear then, that the transducer portion of the tachometer system must perform in the same environment as the rotating shaft.

The auxiliary circuitry, as here defined, consists of electrical excitation sources, amplifiers, demodulators, counters, special power supplies, or other circuitry required to convert the electrical output of the transducer to a useful form and level. The auxiliary circuitry need not be in the shaft environment.

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157 Viskanta, V. Z., "A Study of Rotary Speed Measuring Techniques," Armour Research Foundation (WADD TR 60-210), February 1960, pp. 1-3. AD257998

Table 2-9 . True Mass Flowmeters

Manufacturer	Operating Principle and (Output)	Max. Flow, Density and Temp. Range	Accuracy	Remarks
Control Engineering Corporation Norwood, Mass.	Am(A, E)	3×10^4 pph 0 to 160°F	±1/2% R ±1/4% I	No longer produced
Decker Corporation Philadelphia, Pa.	V, G, R (A, E)	6×10^4 pph, any density	0.36%*	Needs no rotating seals
General Electric West Lynn, Mass.	Am (A, E)	1.2×10^4 pph	"0"	Impeller-restrained turbine type.
Pioneer-Central (Bendix)	Am (A, E, Tot)	6×10^4 pph	0.1%*	Insensitive to temperature, desnity and acceleration.
Potter Aeronautical Union, N. J.	T (D, E, R, I)			Twin turbine type.

* of full scale

A - Analog
Am - Angular Momentum
D - Digital
E - Electronic Read-out
G - Gyroscopic

I - Integrated Rate
R - Rate
T - Turbine
Tot - Totalizing
V - Vibrating

The output device may be an indicator, recorder, or signal converter (the latter to convert a generally usable electrical signal to a specific form suitable as an input to a specific device, such as a subcarrier oscillator or multiplexer of a telemetry system.

Rotary speed transducers may be classified as either analog or digital. In an analog type transducer the amplitude of the intelligence signal is a function of rotary speed (usually proportional over the useful speed range); in a digital type transducer, the frequency, repetition rate, or time interval between peaks, of the intelligence signal is proportional to the rotary speed. Most conventional tachometer systems are of the highly-developed analog type. However, since digital tachometer transducers are much less sensitive to environmental variations, the emphasis of this discussion will be placed on digital tachometer development.

b. Analog Transducers (Ref. 158)

(1) General

Tachometer systems which have been most widely used in the past employ analog transducers, i.e., an electrical signal is generated or an excitation voltage is modulated in such a way that the output voltage or modulation amplitude is a function of shaft rotary speed. Through the years, these instruments have been improved to meet increasingly stringent performance requirements. As a result, these devices are satisfactory for many applications, and may be preferred for some, since minimum tachometer system size and complexity may be attained using analog techniques.

Among the electrical tachometer transducers of importance are the ac induction tachometer, the drag-torque tachometer, the dc tachometer, and the permanent magnet alternator.

(2) AC Induction Tachometer

The conventional ac induction tachometer is essentially a variable coupling transformer in which the coupling coefficient is proportional to rotary speed. One phase winding of the unit is excited

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158 Ibid., pp. 5-6.

by an ac voltage (line or supply frequency), and an ac voltage at excitation frequency and proportional in amplitude to the rotary speed is obtained at the output phase winding. Rotation with the shaft of the rugged squirrel cage or drag cup rotor produces the shift in flux distribution on which the principle of operation of the device is based. For auxiliary equipment, the device requires a source of excitation voltage that is stable in amplitude and frequency.

This tachometer is not suited to telemetry applications and, therefore, will not be further discussed herein.

(3) Drag-Torque Tachometer

The drag-torque tachometer consists of a permanent magnet mounted on the rotating shaft and inside a metallic dish or cup. The rotating magnet produces an eddy current torque on the cup which is proportional to the shaft speed. If the cup is mounted on good bearings and is restrained by a precision spring, the angular deflection of the spring may be measured electrically to provide an analog representation of shaft speed.

Since this transducer requires a second transducer to convert displacement (angular deflection of the spring) to an electrical signal, it is not well suited for telemetry purposes and will not be further discussed herein.

(4) DC Tachometer Generator

The conventional dc tachometer is essentially a small permanent magnet or separately excited generator. The permanent magnet type requires no auxiliary equipment; the separately excited type requires a dc source. One of the chief advantages of the ac tachometer is high gradient (volts per rpm, 10 to 20 volts per 1000 rpm attainable) in a very small size. One of the main disadvantages is that a commutator and brushes are required. Brushes involve operating problems (brush vibration, and arcing, particularly at altitude) and maintenance problems (moisture, deposits of brush carbon on the commutator, brush and commutator wear).

For applications where the direction of shaft rotation must be telemetered, the dc tachometer generator is useful since its

output polarity is dependent upon rotational direction. The output voltage of the permanent magnetic type may be calibrated to provide an accuracy of 0. 25 - 0. 1% of the maximum rpm rating.

(5) Permanent Magnet Alternator

The permanent magnet alternator is similar to a constant field synchronous generator and produces a linear output voltage proportional in amplitude and frequency to shaft speed. Performance is said to be poor at low speeds. With rectifier auxiliary circuitry on the output, dc voltage proportional to speed over a wide range (not approaching zero) can be obtained without brushes or sliding contacts.

The frequency characteristic of its output provides a more accurate measurement of rotational speed since it is unaffected by loading, temperature variations resulting from ambient conditions and self-heating, and armature misalignments caused by shock and vibration. Through use of external circuitry, the frequency may be converted to a proportional dc voltage. This voltage may be utilized for controlling a voltage-controlled oscillator of a frequency-division telemetry system or applied to the multiplexer of time-division systems. Figure 2-62 shows two possibilities wherein amplitude variations (as a function of rotational speed) are removed by a limiter or multivibrator. The output of this device may then be fed through a dc restorer circuit, an integrator, and a filter to provide a single-ended dc voltage which is linear with generator speed and has zero output at zero speed. Figure 2-62 also shows that the amplitude-limited signal may be fed through a low-pass filter to a frequency discriminator. The filter eliminates harmonics of the fundamental frequency which result from the amplitude limiting function. The discriminator output may provide a double-ended dc voltage with zero output occurring at a specific frequency (speed of rotation). Thus, variations about this pre-selected frequency may be telemetered, rather than the actual frequency. Of course, numerous variations of the circuitry shown in Figure 2-62 are possible and the complete frequency-to-dc conversion may be accomplished in an extremely small volume through use of transistors and miniaturized packaging techniques.

The permanent magnet alternator may also be used for the measurement of speed differences by connecting the outputs of two speed measuring circuits to a differential bridge as shown in Figure 2-63. The indicated difference speed is independent of the actual speeds.

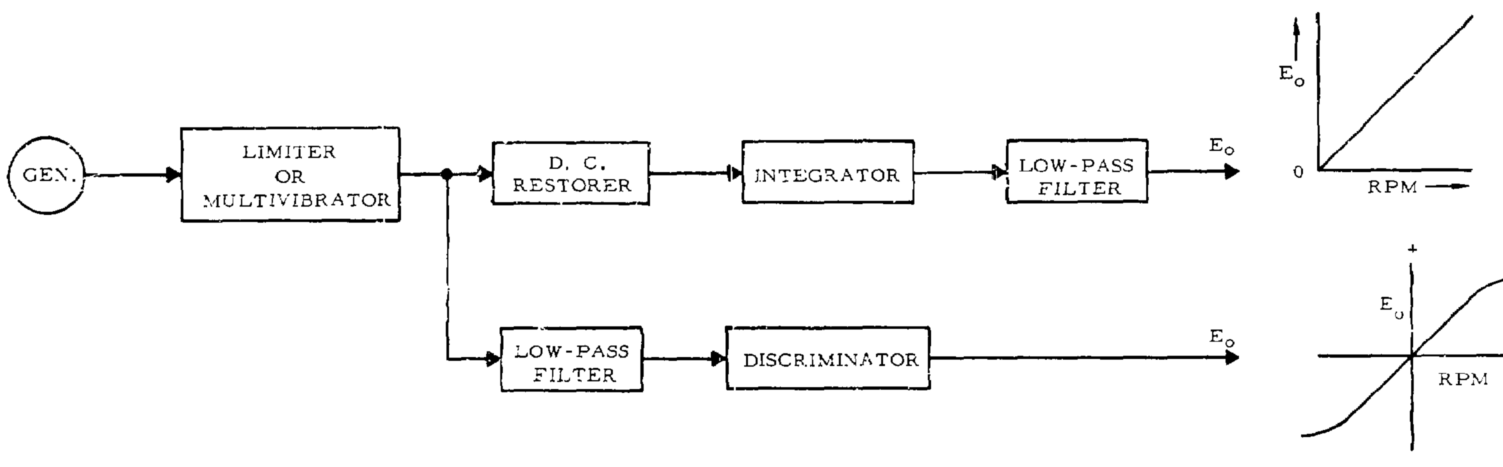


Fig. 2-62. Conversion of Frequency to DC Voltage

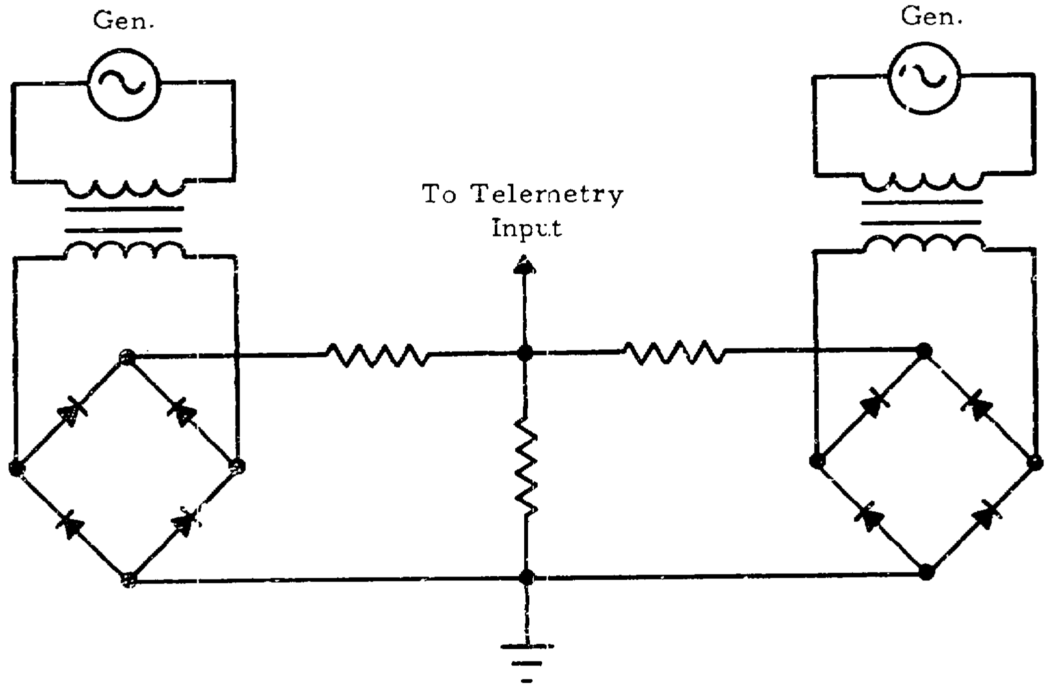


Fig. 2-63. System Employing Two Permanent Magnet Alternators for Measuring Differential Speed

c. Digital Transducers (Ref. 159)

(1) General

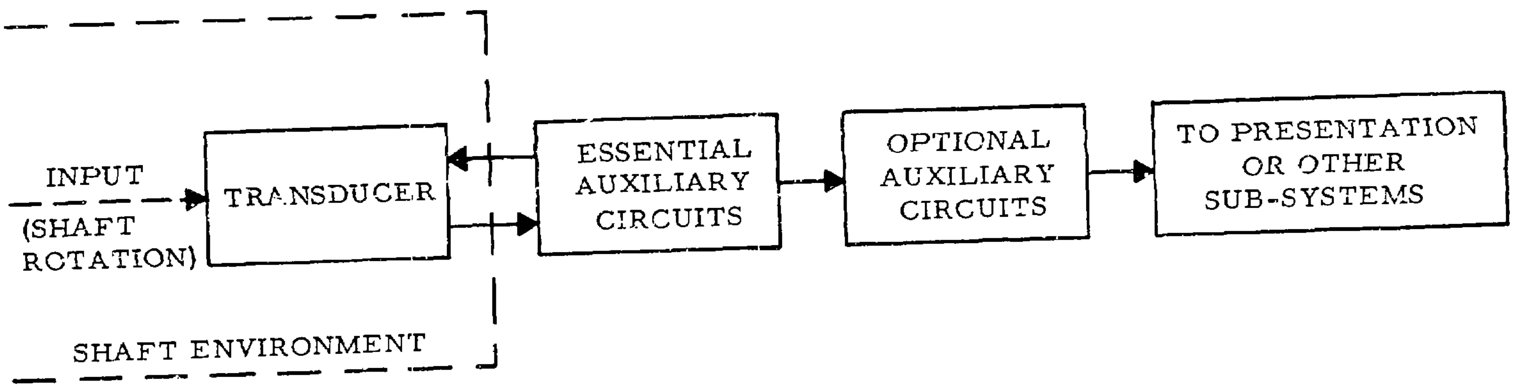
The units of measurement of shaft speed are events per unit time. The units most often used are revolutions per minute (rpm). With the availability of electronic counting circuitry and precise time interval measurement circuitry, digital measurement of shaft speed can be accomplished readily. If a reference mark or some discontinuity in a readily measurable physical property is placed on or in the shaft, the speed of which is to be measured, the number of passages of the reference mark or discontinuity past a fixed sensing element in proximity to the shaft per arbitrary unit of time will provide a measure of shaft speed. If a number of reference marks or discontinuities are placed uniformly around the periphery of the shaft, fractions of a revolution can be detected and counted.

For purposes of description, a digital tachometer system is considered to be composed of a transducer, essential auxiliary circuits, and optional auxiliary circuits (such as indicator or encoder) as shown in block diagram in Figure 2-64.

The function of the transducer is to convert shaft rotation into an electrical signal representing rotary speed. For a digital tachometer system, the transducer consists of an appropriate sensing element in proximity to the shaft, and reference marks or discontinuities incorporated in or attached to the shaft. The essential auxiliary circuits or devices include an energy source and any circuitry required for proper sensor operation. The optional auxiliary circuitry is that required to obtain a digital indication, an appropriate digital code at the proper sampling rate for input to other digital equipment, and/or digital-to-analog conversion or frequency-to-voltage conversion for analog input to telemetry equipment.

The energy source is generally an essential auxiliary circuit, although it may be part of the transducer (as in the case of a permanent magnet generator). The transducer performs the functions of modifying the energy supplied by means of the discontinuities on the shaft, and of sensing the modified energy. Only the transducer need be in the region of extreme temperature and radiation environment; i. e., part of the transducer

159 Ibid., pp. 9-13.



TRANSDUCER

1. DISCONTINUITY ON SHAFT
2. SENSOR IN PROXIMITY TO SHAFT

ESSENTIAL CIRCUITS

1. EXCITATION SOURCE
2. SIGNAL AMPLIFIERS

OPTIONAL CIRCUITS

1. TIME INTERVAL COUNTER AND DIGITAL INDICATOR
2. FREQUENCY OR PULSE RATE TO ANALOG VOLTAGE CONVERTER
3. DIGITAL COUNTER ENCODER
4. OTHERS AS DESIRED

Fig. 2-64. Block Diagram of Digital Tachometer System

is on the shaft (the discontinuities) and part is in proximity to the shaft (the sensor). The essential and auxiliary circuits and devices can be remote from the shaft environment without significant degradation of information from the sensor.

(2) Features of Digital Tachometer Systems

An ideal digital tachometer system would consist of a transducer which would produce one pulse or one cycle of alternating current for every time a shaft discontinuity passed the fixed sensor element, with signal amplitude constant, independent of shaft speed, environment, and circuit variables. The essential auxiliary circuits, in addition to providing excitation or power to the device, would consist of means for recognizing one pulse or one cycle of the transducer output. If signals are of constant or near constant amplitude, the recognition circuits can be much simpler in design than if the signals vary widely in amplitude. A choice could then be made of appropriate optional circuitry to count and display or encode the number of pulses or cycles per unit time, or to convert the signal repetition rate to an analog voltage amplitude.

If the signal amplitude varies due to extraneous factors such as environmental changes, the system will remain operative and accurate as long as the signal amplitude does not drop below the level of system noise or below the threshold of the recognition circuits, and as long as the signal amplitude does not increase to the point where auxiliary amplifiers are overloaded. This allows a wide range of operating conditions inherently, which an analog transducer system, in general, does not. In addition, feedback techniques may be employed in some situations to extend the operating range by adjusting transducer excitation or signal preamplifier gain to maintain the signal level nearly constant or at least inside the range of the recognition circuit.

Important criteria for digital shaft speed transducers are the signal-to-noise ratio and amplitude difference between the two states of the transducer (pulse and no-pulse, or maximum and minimum values of alternating signals). As long as the auxiliary circuitry can distinguish between two states, the number of changes of state (that is, shaft revolutions or sub-intervals of a revolution) can be counted per unit time. Therefore, the accuracy, resolution, and dynamic range of the tachometer system will depend to the greater extent on the characteristics of the auxiliary circuits and not on the transducer. Although the transducer, being in the shaft environment, may be subjected to environmental extremes, the auxiliary

circuit can be located at a distance from the transducer in a more moderate and, possibly, controlled environment. Amplitude or phase degradation of signals due to the leads or lines between transducer and circuits will not affect performance as long as the degradation is not so extreme as to mask the signals entirely.

In summary then, the digital technique applied to tachometer systems permits some further design freedom on the transducer and broadens the range of signal amplitude variation that is permissible, at the expense of some additional external circuitry.

(3) Transducer Types

The most important distinguishing feature in the various types of transducers is the type of energy that is utilized. Sensors using electric (ac capacitive), electrostatic (dc capacitive), magnetic (eddy current, variable reluctance, permanent magnet), electromagnetic (microwave, light) acoustic (sound waves, pneumatic impulses) and nuclear energies have been devised; however, some are not suitable for use in military flight vehicles. Several types are discussed in the following paragraphs. A comparison of digital rotary sensors is presented in Table 2-10 (Ref. 160).

(4) Capacitive Tachometer Transducer (Ref. 161)

(a) General

For measurement of rotary speed, a dynamic capacitor or capacitive transducer element with capacitance a function of shaft position can be constructed in a number of ways. A simplified sketch of a complete capacitive transducer is given in Figure 2-65. The capacitor is formed by the metallic stator plate and a rotor plate which is attached to the shaft. The capacitor has maximum capacity for the shaft position illustrated in Figure 2-65, and minimum capacitance for a shaft position rotated 180° (corresponding to the broken line). To convert the cyclical variations of capacitance into an electrical signal, an excitation source E and resistor R are also shown.

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160 Ibid., p. 90.

161 Ibid., pp. 19-36.

Table 2-10. Comparison Table for Digital Transducers

Sensor	Maximum Temperature °C	Maximum Radiation Dose	Relative* Resolution	Relative Complexity	Comments
Capacitive	1000	---------	G	Simple	Performance is deteriorated by neutron flux.
Variable Reluctance	800	$10^{18} n/cm^2$	G	Simple	Maximum temp. limit is due to decrease of permeability; either normalized resolution or range may be limited by the maximum frequency that could be used for excitation.
Eddy Current	1000	$10^{18} n/cm^2$	G-	Simple	Available magnetic wire is limited to a temp. of 650°C; above this temp. size increases and normalized resolution decreases with increasing temp. rating.
Permanent Magnet Generator	800	$10^{18} n/cm^2$	G	Self-generating	Maximum temp. limit is due to loss of magnetic properties. Signal amplitude depends on speed.
Permanent Magnet-Vacuum Tube	800	--------	G	special tubes required	Tubes for temp. range -195 to +750°C are under development; nuclear radiation effect on the cathodes of these tubes is not known.
Optical	200	$10^{14} n/cm^2$	E	Simple	Maximum temp. and nuclear radiation limits are due to detectors; possibly the detector and source can be located outside extreme environment.
Microwave	200	$10^{14} n/cm^2$	G-	Requires elaborate source, waveguide, and detector system	Signal amplitude decreases with increasing nuclear radiation flux; temp. limited by the detector; the detector and Klystron may possibly be located outside the extreme environment.
Acoustic	1000	$10^{18} n/cm^2$	G	Double energy conversion	Sensitive to altitude, temp., radiation, vibration. Generally not suitable.
Pneumatic	1000	$10^{18} n/cm^2$	G	Complex	The sensor having a source of compressed gas, a chopper type rotor, and a remote dete...r is assumed.
Radioactive	200	---------	G	Complex	Signal amplitude decreases with increasing speed which may limit speed range. Detectors temp-limited. Radiation background problem.

* E - Excellent

G - Good

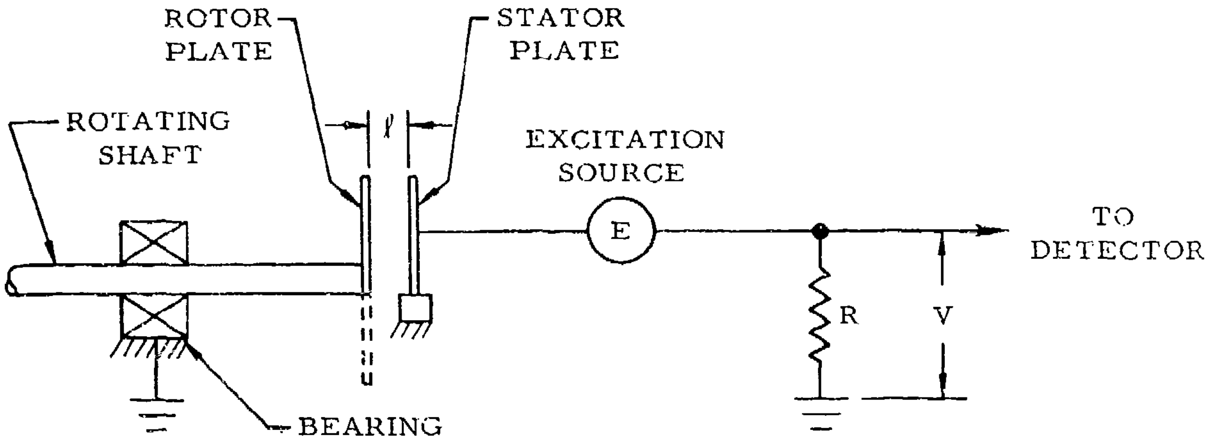

Fig. 2-65. A Simplified Sketch of a Variable Position Capacitive Transducer

(b) Transducer Structures

There are two techniques that can be used to produce capacitance variation as a function of shaft position: the relative position of the capacitor plates can be varied, or the dielectric constant between the plates can be varied. The capacitor shown in Figure 2-65 is a simple variable position capacitive transducer element. Such a capacitor can be used only where the rotating shaft makes electrical contact through the bearings to some stationary part of the equipment which is electrically grounded. Since an electrical connection through a bearing is generally unreliable, a split-stator capacitor which does not require electrical contact with the rotor plate(as illustrated in Fig. 2-66) is preferred.

A variable dielectric constant transducer results if, instead of a metallic plate in the split stator configuration, a rotor having a higher dielectric constant than the ambient fluid medium between the plates is used. In this case, the effective dielectric constant is a function of rotor position and the capacitance varies cyclically for every revolution or fraction of a revolution. Since dielectric materials are more affected by changes in environment than are metals, the following discussion will place emphasis on the split-stator variable position transducer.

The number of transducer structure geometries or configurations that can be used is virtually unlimited. Sketches of a number of configurations are shown in Figures 2-67 through 2-70. In all the diagrams, the capacitance rotor consists of a modification of a portion of the shaft. Since a given shaft may have a smaller diameter, lower electrical conductivity, or higher interfering magnetic permeability than would be desired for the transducer, the shaft geometry modification can be obtained by attaching a disk of appropriate shape and material to the shaft.

The sketches show only variable position capacitors. However, for the split-stator arrangements, the rotor could be replaced by a high dielectric material, producing a variable dielectric transducer.

(c) Transducer and Auxiliary Circuits

There are three basic techniques that can be used to convert capacitance variations to voltage: (1) the dc excited capacitive transducer which can be considered as an electrostatic generator, (2) the ac excited transducer which involves measurement of impedance, and (3) the use of the transducer capacity in the tank circuit of an oscillator thus obtaining a frequency modulated signal. The intelligence signals can then be amplified and demodulated to provide an appropriate signal to a telemetry system.

A general capacitive transducer circuit using ac excitation is shown in Figure 2-71. This is essentially an electrostatic generator because the voltage across the capacitor increases as the plates are separated.

An approximate solution of the circuit shown in Figure 2-71 can be obtained if it is assumed that the charge on C remains approximately constant during one cycle of capacitance variation. This condition requires that the time constant RC in seconds should be much larger than 60/nP which, at low rotary speeds, may be difficult to fulfill. Assuming that capacitance varies sinusoidally and initial capacitance is C_o, the amplitude and frequency (but not the waveform) of the generated ac potential is given by

$$V = \frac{2 E C_o \hat{C}}{C_{max} \; C_{min}} \cos \omega_m t \qquad (2\text{-}31)$$

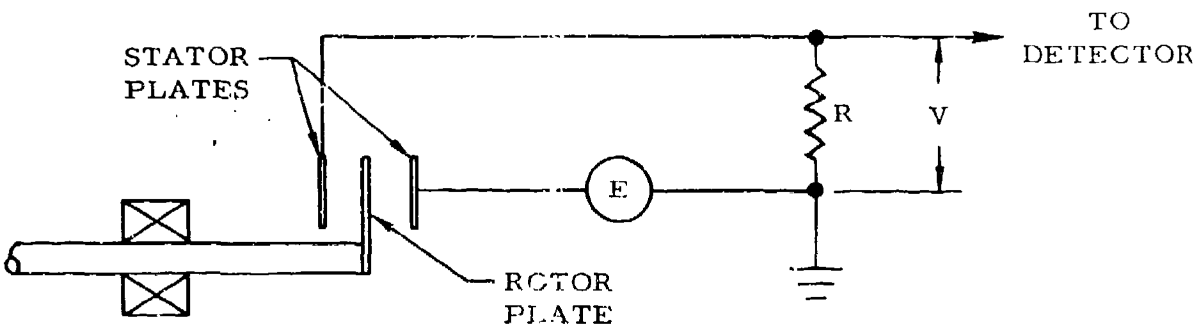

Fig. 2-66. A Simplified Sketch of a Split-Stator Capacitive Transducer

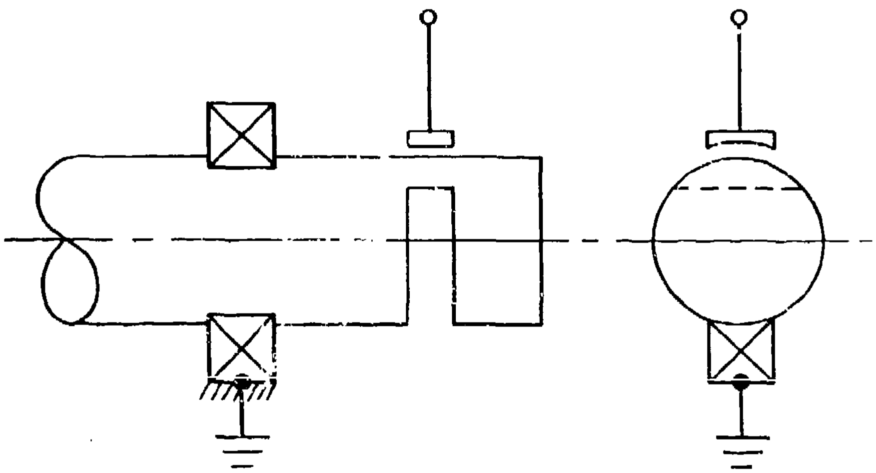

Fig. 2-67. Sketch of Simple Structure

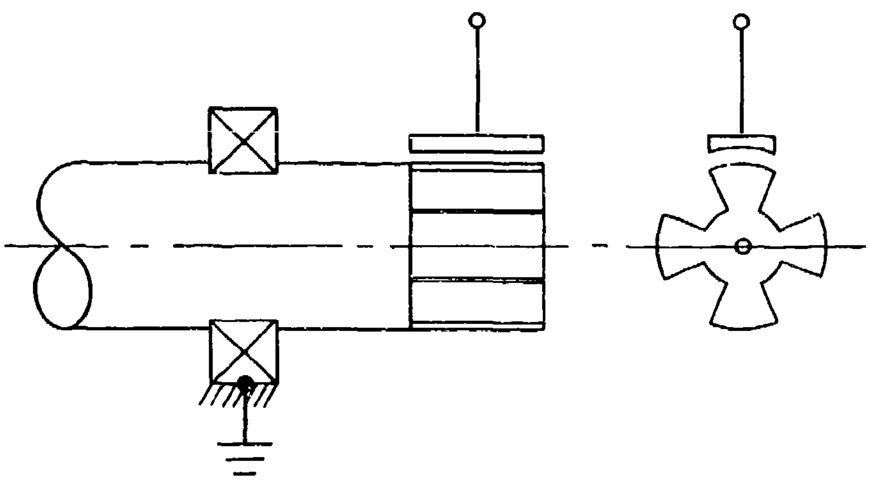

Fig. 2-68. Sketch of Gear Type Structure

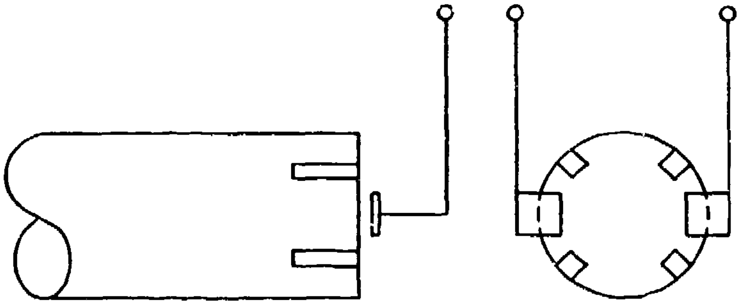

Fig. 2-69. A Simplified Sketch of a Variable Position Capacitive Transducer

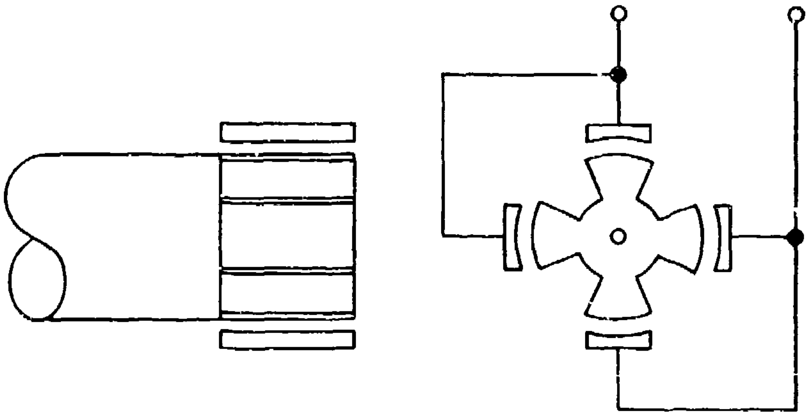

Fig. 2-70. Sketch of Split-Stator Gear Type Structure

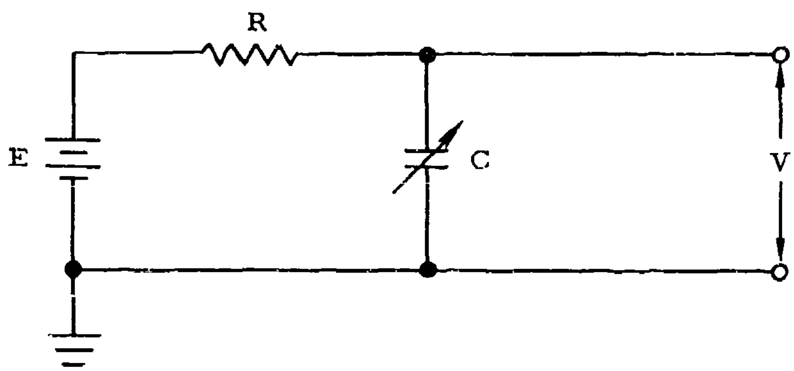

Fig. 2-71. Electrostatic Type Circuit Schematic Diagram

where

V = generated signal in volts

E = excitation potential in volts

$C = C_o + \hat{C} \cos \omega_m t$

$C_o = 1/2\ (C_{max} + C_{min})$

$\hat{C} = 1/2\ (C_{max} - C_{min})$

C_{max} = maximum transducer capacity

C_{min} = minimum transducer capacity

$\omega_m = (\pi/30)\ nP$ in radians

n = speed in rpm

P = resolution or number of capacity changes per revolution

Thus, the amplitude of the output signal for an ideal transducer at high shaft speeds is determined by the percent change in capacitance and is constant.

If the peak to peak ac component of the voltage across the transducer capacitor is small in comparison to the dc component, (short RC time constant), the generated voltage is

$$V = \frac{-10^{-6}\ \pi}{30}\ n\ E\ P\ \hat{C}\ R_L \sin \omega_m t \qquad (2\text{-}32)$$

where

R_L = load resistance in megohms

Experimental work by the Armour Research Foundation has shown that equation (2-32) is approximately valid at low speeds, and therefore, the amplitude of the generated signal at low speeds is proportional to the change in capacitance and to shaft speed (Ref. 162). From analysis

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162 Ibid., p. 26.

and experiments, it has been found that the dc excited capacitance rotary speed sensor does not meet the requirement of the ideal sensor for a digital sensor at low speed, even though signal frequency is proportional to shaft speed, since signal amplitude varies with speed. Thus, the lower limit of dynamic range of this class of sensor in a digital system would depend on the voltage threshold of the signal recognition circuit rather than on the least count of the optional auxiliary circuit. The dc excited capacitance transducer can be used as an analog system, since peak to peak signal amplitude is proportional to shaft speed, but only in the speed range above the point where signal amplitude is great enough to be readily measurable and below the region in which signal frequency approaches the reciprocal of the time constant of the circuit.

A simple ac excited capacitive transducer is shown in Figure 2-72. A physically small transducer will necessarily result in small voltage variations because of the inherent low percentage change

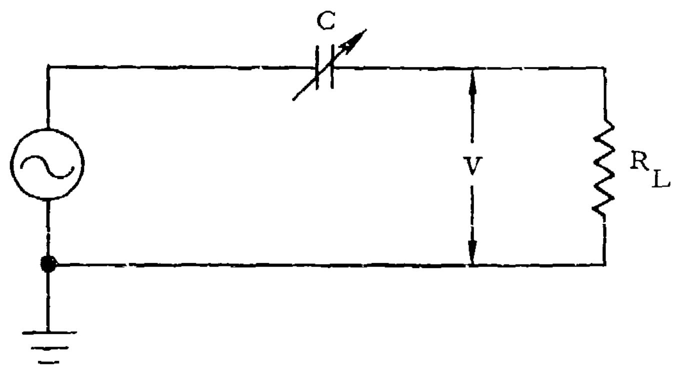

Fig. 2-72. Schematic Diagram of Simple AC Excited Transducer Circuit

in capacitance. For this reason, a sensitive impedance measurement circuit is desired. A parallel resonant bridge may be used; however, it is sensitive to environmental changes because the impedance of the arms depends on the Q of the circuit elements. A simple circuit for detection of amplitude modulated signals is shown in Figure 2-73. The detector circuit is only given for the purpose of illustration. In case small changes of capacitance must be measured, additional stages of amplification may be required. Since the modulation frequency is proportional to shaft speed, and modulation

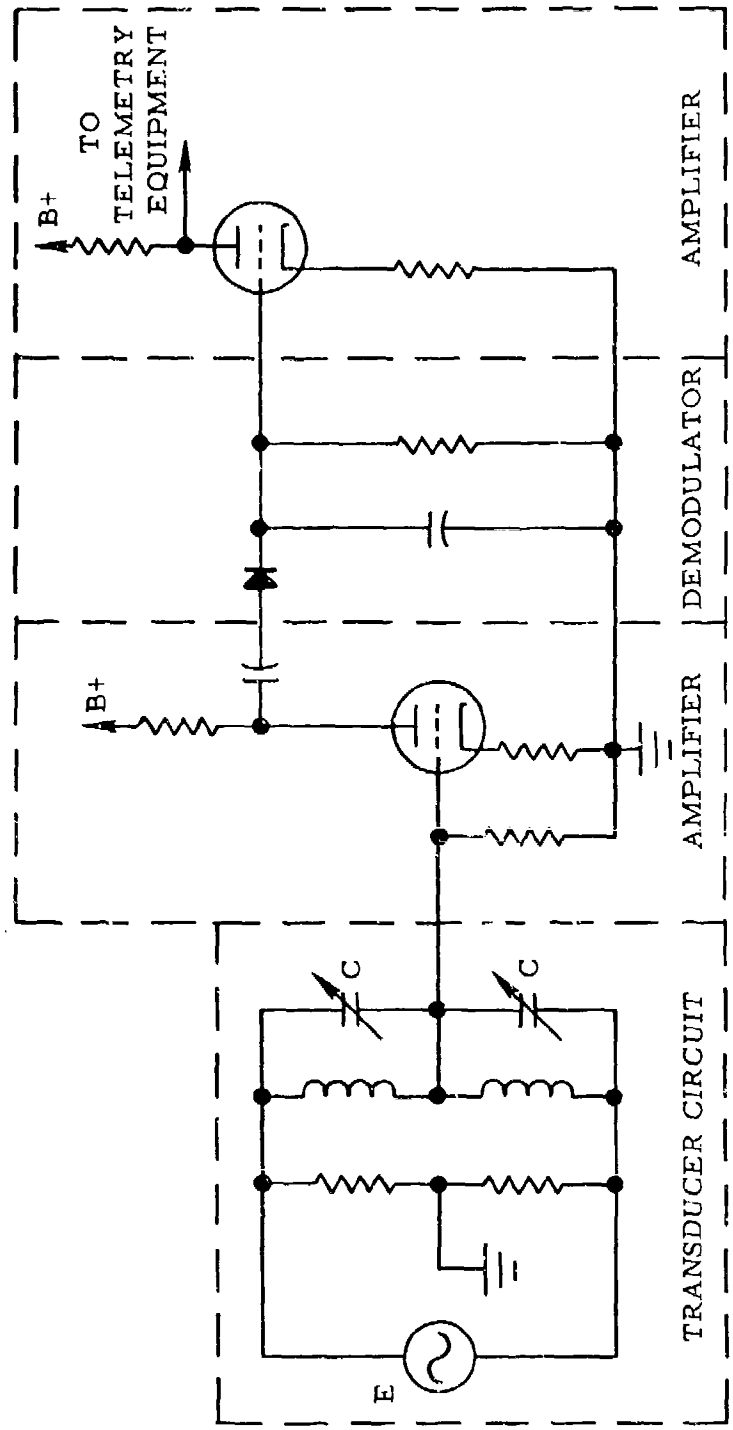

Fig. 2-73. Schematic Diagram of a Capacitive Tachometer Transducer Circuit

frequency is proportional to shaft speed, and modulation amplitude is relatively constant with speed, the ac excited capacitance transducer meets the general requirement for a digital-type tachometer system.

In the oscillator-type circuit, the transducer capacitor may be used in the tank circuit to cause frequency modulation of the oscillator's output signal. In this system, the oscillator frequency varies with shaft position and shaft speed is indicated by the rate at which frequency changes. In addition to the oscillator, auxiliary circuits are required to demodulate the fm signal, to count the number of frequency changes (maxima to minima) per unit time, and to convert the count to a digital code which is suited to telemetry systems.

Another technique using the oscillator-type circuit is to utilize the change in Q due to capacitance change with shaft position. If the nominal oscillator frequency is much higher than the frequency equivalent of the shaft speed, the oscillator gain may be selected such that oscillations are sustained only when the tank circuit Q is a maximum. In this mode of operation, the oscillations start and stop as capacitance varies due to shaft rotation. A count of the number of bursts of oscillations per unit time provides a measure of shaft speed. The variable Q circuit is not suitable for a nuclear radiation environment because the presence of neutron flux causes a decrease in the capacitor's leakage resistance and a corresponding decrease in Q occurs.

(5) Variable Reluctance Tachometer Transducers (Ref. 163)

(a) General

The reluctance of a high permeability magnetic circuit of uniform cross section can be approximately expressed by

$$R = \frac{\ell}{\mu_e A} \qquad (2\text{-}33)$$

where

R = reluctance (gilberts/maxwell)

A = cross-sectional area (cm^2)

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163 Ibid., pp. 37-48.

ℓ = average length of the core (cm)

μ_e = effective permeability of the circuit (gauss/oersted)

In this application, it is convenient to consider that μ_e is varied by bringing magnetic material in proximity to the magnetic circuit. The length of the core ℓ and the cross-sectional area A are assumed to be fixed. In order to produce large percentage changes in reluctance, it is necessary to have an air gap in the high permeability magnetic core. The approximate effective permeability of such a circuit is

$$\mu_e = \frac{\mu_m}{1 + \left(\frac{a_e}{\ell}\right) \mu_m} \qquad (2\text{-}34)$$

where

μ_m = permeability of core material (gauss/oersted)

a_e = effective air gap length (cm)

The effective air gap length can be varied by introducing high permeability magnetic material in the gap or in the proximity of the gap.

If a coil is wound around the core, the potential induced in it due to the rate of change of flux is

$$V = -10^{-8} N \frac{d\phi}{dt} = -10^{-8} N \frac{d}{dt} \left(\frac{F}{R}\right) \qquad (2\text{-}35)$$

where

V = potential induced in the coil (volts)

N = number of turns

F = NI = magnetomotive force (gilberts)

The coil inductance may be expressed by

$$L = N^2/R \qquad (2-36)$$

where

L = coefficient of inductance

It is seen from equations (2-35) and (2-36) that reluctance can be determined from induced potential or inductance. Bridge and oscillator circuits may be used for the measurement of inductance. They are similar to those previously described for the measurement of capacitance and, therefore, will not be described in connection with variable reluctance transducers.

(b) Transducer Structures

A variable reluctance transformer type tachometer transducer is illustrated in Figure 2-74. For the rotor position shown in Figure 2-74, the reluctance is minimum and the potential induced in the secondary winding is maximum. Numerous other configurations may be used. Figure 2-75 shows a gear type chopper structure and Figure 2-76 shows a differential transformer with a similar type chopper.

Assuming sinusoidal variation of permeability, regulated current source, and equal permeability of the chopper and core, equation (2-35) for a dc excited transducer can be reduced to

$$V = (10^{-8}/\ell)\, N_1 N_2\, IA\, \hat{\mu}_c\ \omega_m \sin \omega_m t \qquad (2-37)$$

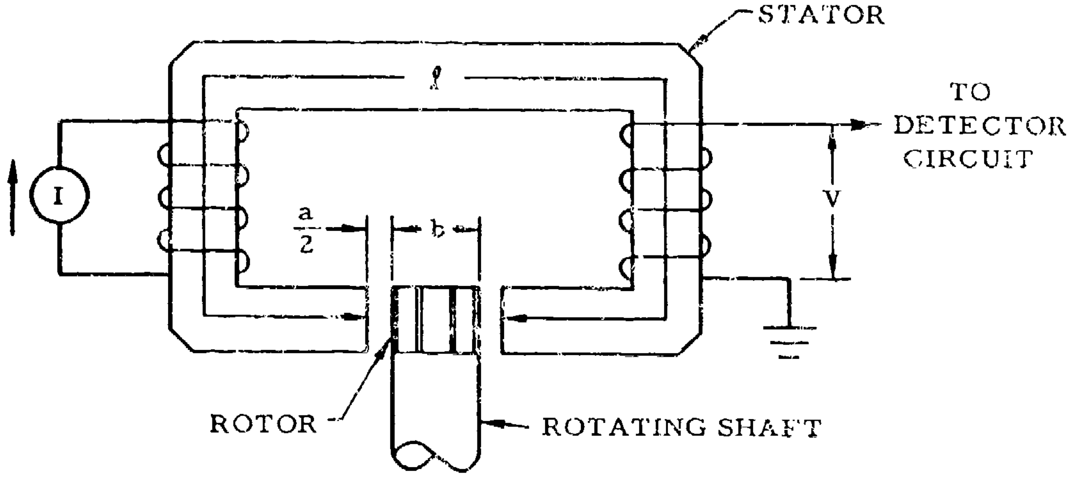
where

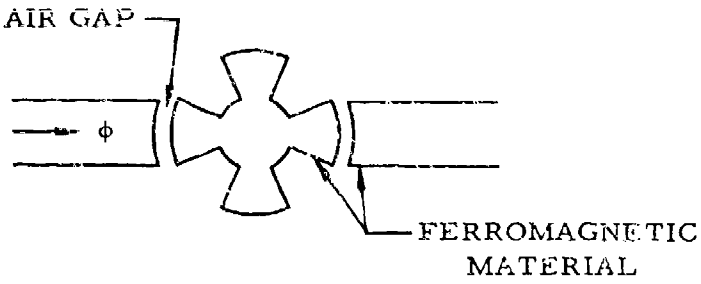
I = excitation current (amperes)

N_1 = number of turns on the excitation winding

N_2 = number of turns on the output winding

$\omega_m = (2\pi/60)\, nP$ (radians)





END VIEW OF THE ROTOR

Fig. 2-74. Variable Reluctance Transducer

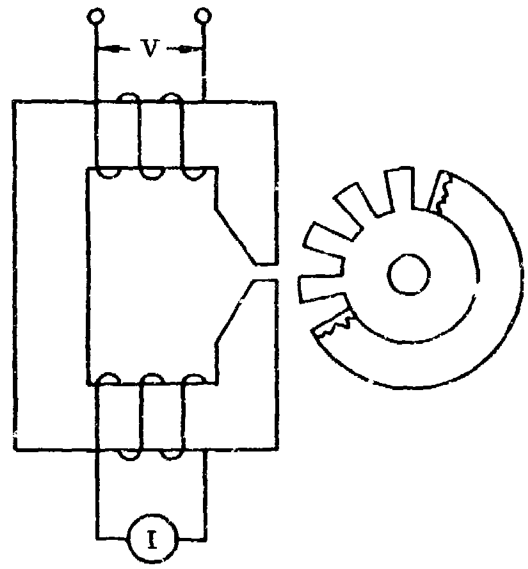


Fig. 2-75. Gear Type Chopper Transducer Structure

P = resolution or number of reluctance changes per shaft revolution

$\mu_e = (\mu_{eo} + \hat{\mu}_e \cos \omega_m t)$

$\hat{\mu}_e = (1/2)(\mu_{e\,max} - \mu_{e\,min})$

$\mu_{eo} = (1/2)(\mu_{e\,max} + \mu_{e\,min})$

For high permeability core and chopper, i.e., for $\mu_m \gg (\ell/a)$, $\hat{\mu}_e$ can be calculated from equation (2-34) and is approximately equal to

$$\hat{\mu}_e = \frac{b(\ell + a)}{2a\,(a - b)} \qquad (2\text{-}38)$$

where (See Figure 2-74)

a = actual air gap length (cm)

b = thickness of chopper (cm)

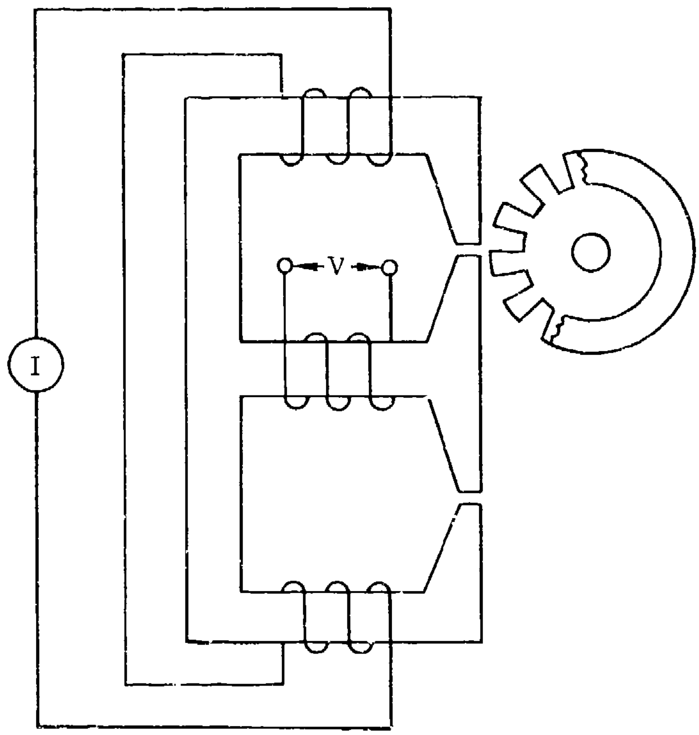


Fig. 2-76. Differential Output Transducer Structure

For the ac excited transducer case, the induced potential in the secondary is a function of the effective permeability and is approximately equal to

$$V = (10^{-8}/\ell)\, N_1 N_2 A I_c\, \mu_{eo} \Big[\omega_c \sin \omega_c t \left(1 + \frac{\hat{\mu}_e}{\mu_{eo}} \cos \omega_m t \right) + \frac{\hat{\mu}_e}{\mu_{eo}}\, \omega_m \sin \omega_m t \sin \left(\omega_c t + \frac{\pi}{2} \right) \Big] \quad (2\text{-}39)$$

where

$$I = I_c \cos \omega_c t = \text{excitation current (amperes)}$$

For measurement of low speeds and/or low resolution, it may be assumed that $\omega_c \gg \omega_m$ and equation (2-39) reduces to

$$V = (10^{-8}/\ell)\ N_1 N_2 A I_c \mu_{eo}\ \omega_c$$

$$\sin \omega_c t \left(1 + \frac{\hat{\mu}_e}{\mu_{eo}} \cos \omega_m t\right) \qquad (2\text{-}40)$$

Equation (2-40) is for an amplitude modulated signal and the modulation index is (See Figure 2-74)

$$\frac{\hat{\mu}_e}{\mu_{eo}} = \frac{ab + b}{2a + ba - b\ell} \qquad (2\text{-}41)$$

It is seen that the percent modulation is limited by the minimum spacing between the rotor and stator. For an ideal differential output transformer (See Figure 2-76), the steady-state component of the output signal (the component of the output which is independent of rotary speed) is cancelled and the unity in brackets of equation (2-39) drops out. The output voltage from an ideal differential transformer, therefore, is a suppressed carrier type signal. Smaller percent changes in reluctance can be detected using the differential output transducer than the ordinary transformer circuit.

(c) Magnetic Sensor (Ref. 164)

From the preceding discussion, it is apparent that the variable reluctance transducer requires both a chopper and sensor. The following paragraphs provide information on a particular type of sensor.

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164 Elam, David and Lloyd A. Thacher, "Magnetic Pickups -- Operation and Applications," Electrical Manufacturing (June, 1960).

This is presented by way of example, and it is not implied that the description or characteristics are typical of all such sensors available from manufacturers.

A magnetic sensor consists of a cylindrical permanent magnet with a coil of copper wire wound around it, as shown in Figure 2-77. Generally, to save space, the coil is not wound directly

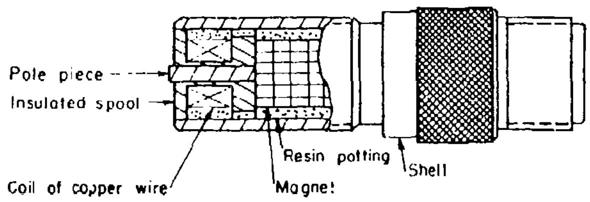

Fig. 2-77. Cutaway View of Magnetic Sensor

on the magnet, but on an insulated spool which slips over a smaller-diameter pole piece that is attached to the end of the magnet. This assembly, typical of those manufactured by Electro Products Laboratories, is resin-potted in a stainless steel, threaded, mounting shell. A special high-temperature cement is used for the potting material if the pickup is to be used in extreme environments.

The magnetic sensor generates an electrical voltage whenever the magnetic field around it is disturbed. The details of this operation are shown in Figure 2-78 where the dashed lines (b) and (f) represent the normal lines of force created by the magnet when there is no extraneous magnetic material in the vicinity. When a piece of magnetic steel is brought near the head of the pickup, the lines of force shift, as represented by the solid lines (b') and (f'). As the lines shift position, they cut across the coil wound on the pole piece and generate a voltage in it.

The output voltage depends upon the rate of change of the magnetic field. This in turn, is dependent on three factors: (1) the clearance between the pickup and actuating medium, (2) the rate of

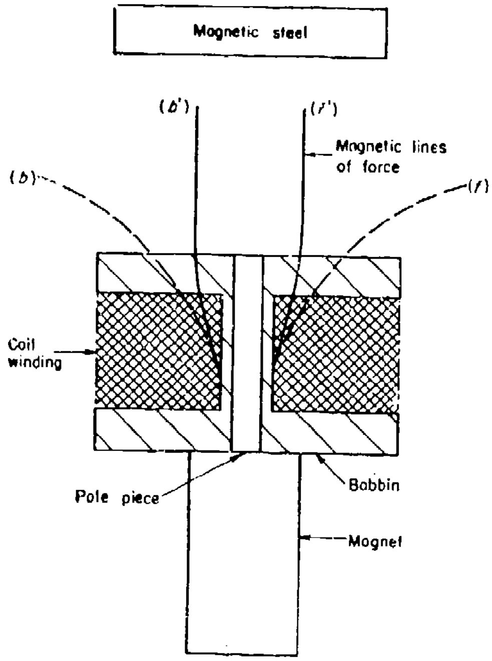

Fig. 2-78. View of Sensor Showing Shifting of Magnetic Lines of Force Due to Disturbance of Magnetic Material.

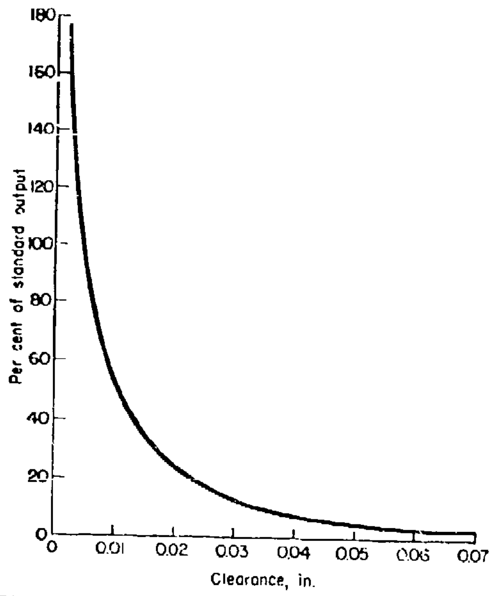

Fig. 2-79. Curve Showing Change in Output of Magnetic Sensor as Function of clearance Between Poles Piece and Activating Medium. Standard output of 100% is assumed for clearance of 0.005".

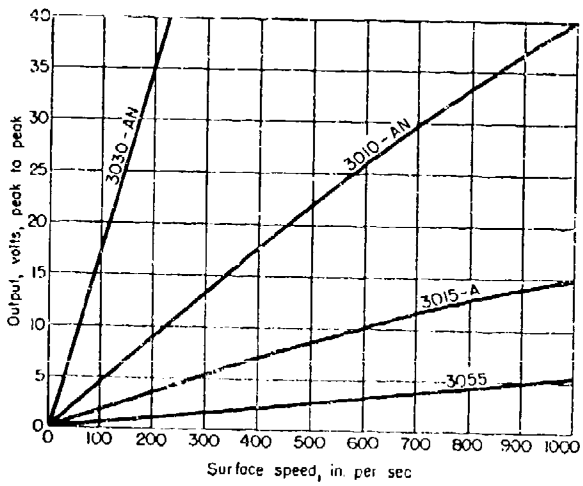

Fig. 2-80. Comparison of Outputs From Standard Sensors (operating under identical conditions with actuating medium being a 20-pitch, 30-tooth, ferromagnetic gear with 0.005" clearance. Load is 100,000 ohms).

movement of the actuating medium, and (3) the size of the actuating medium. As shown in Figure 2-79, output voltage tends to be inversely proportional to the clearance between the head of the sensor and the actuating medium. Output versus speed, for several sensors manufactured by Electro Products Laboratories, is shown in Figure 2-80.

In actual applications, the sensor is actuated by the teeth of a gear, the blades of a turbine, spokes on a wheel, or a steel part such as a screw mounted on or inserted in a moving, nonmagnetic material. The most common application is the measurement of rotary speed from the teeth of a rotating gear. Small-tooth gears (20-pitch or higher) produce an output which is practically a sine wave. Coarser teeth produce a more distorted output, but the peak-to-peak voltage values are higher (Figure 2-81). The outputs for single activating

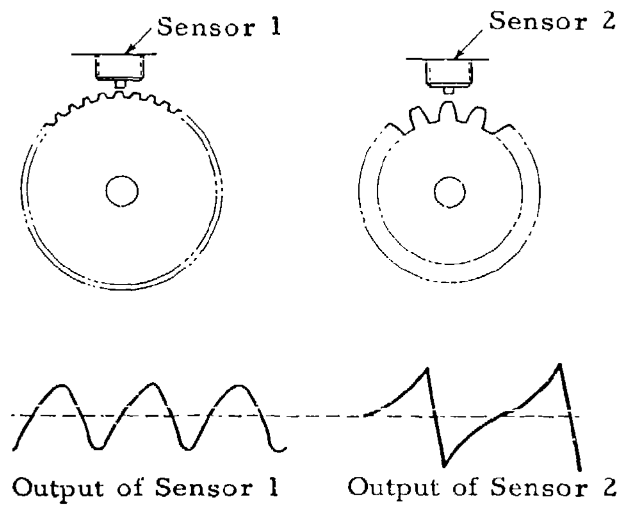

Fig. 2-81. Output Waveforms Produced by Fine- and Coarse-Tooth Gears

masses of two different sizes are shown in Figure 2-82, and it is seen that the sides of the projecting mass influence the shape of the output wave. A straight-sided projection produces a sharp waveform and a projection with a relatively large flat top will produce a waveform having a time interval between positive and negative peaks.

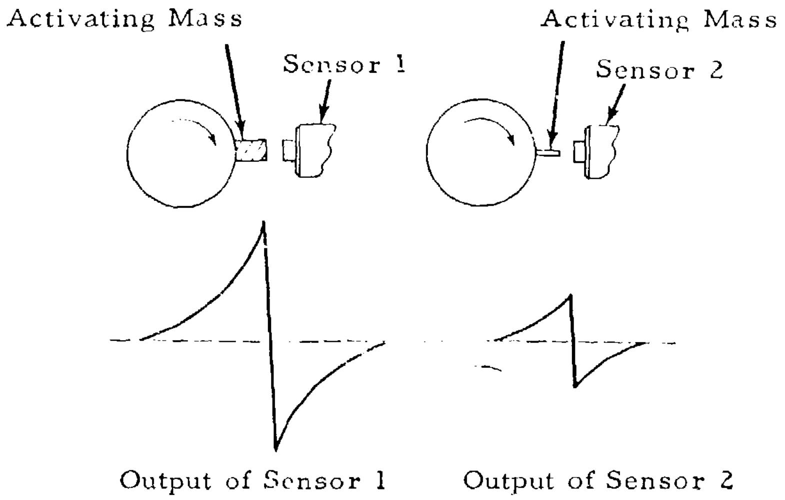

Fig. 2-82. Outputs Produced by Two Sizes of Single Activating Masses

It is desirable to actuate a magnetic sensor with a protrusion from a metallic surface rather than with a keyway or slot in the surface. When one of the latter is used, the sensor is closer to the entire mass of the exciting material and more vulnerable to unwarranted background signal due to varying density or eccentricity of the material. On the other hand, when excitation is from a protrusion, the sensor is a relatively greater distance from the exciting material and less likely to pick up stray signals between excitation periods.

With any given speed and clearance conditions, maximum power output results when the field of the sensor is filled with a relatively infinite mass of magnetic material at one instant and a complete absence of such material at the next instant. Using the notations

in Figure 2-83, this condition can be achieved by making A equal to or greater than B, B equal to or greater than D, and C equal to or greater than 3 x D. These are the optimum conditions.

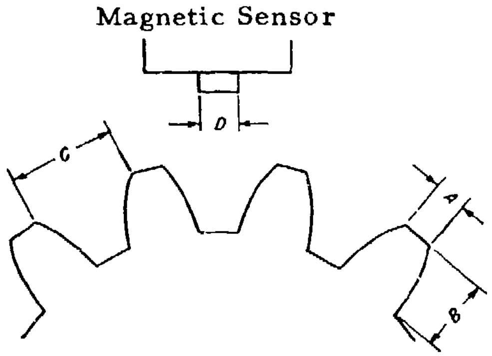

Fig. 2-83. Diagram for Determining Dimensions for Optimum Operation of a Magnetic Sensor

It is possible to excite magnetic sensors through thin sections of non-magnetic substance. This type of barrier is often desirable when the exciting means is in an environment of undesirable liquids or gases, when it is necessary to provide a seal against pressure, or in extremely hot environments. With non-metallic separators, the output of the sensor is affected only by the increased clearance due to the thickness of the separator itself.

Metallic separators between the sensor and the actuating device reduce the output appreciably. This is due to a "shorted turn" effect, since eddy currents are induced in the metallic separator. Loss of output increases with output frequency and becomes very severe at about 5 kilocycles.

(6) Eddy Current Tachometer Transducers (Ref. 165)

(a) General

The parameters of interest in eddy current transducers are inductance and resistance of the air core coil sensors. A conductive element attached to or part of a rotating shaft effects parameter variations as a function of shaft rotation. The current passing through the transducer coil creates a magnetic field and this field induces eddy currents in the highly conductive element which passes near the coil. The eddy currents, in turn have an associated magnetic field which opposes the original field. The superposition of the two fields reduces the effective inductance of the coil. For an element with finite conductivity, there is a power loss due to the eddy currents flowing in the element. As a result of this power loss, the effective resistance of the coil is increased.

A detailed treatment of the eddy current type transducer will not be presented herein. For a detailed analysis and some experimental data, the reader is referred to the above listed reference.

(b) Transducer Structures and Circuit

The structure of one eddy current transducer suitable for measurement of rotary speed is shown in Figure 2-84. The structure is simple since no magnetic materials are used in its construction. The conductive chopper element is attached to a shaft so as to rotate in the proximity of the sensor coil and thus effect a change in inductance.

A gear type structure is shown in Figure 2-85. This has been found to be most suitable from the standpoint of mechanical strength and stability, maximum resolution, and minimum effect of temperature on transducer performance (Ref. 166). In order to increase signal level, multiple coils (up to as many in number as there are teeth on the chopper) can be located around the periphery of the chopper and connected in series.

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165 Viskanta, _op. cit._, pp. 49-72.

166 _Ibid._, p. 64.

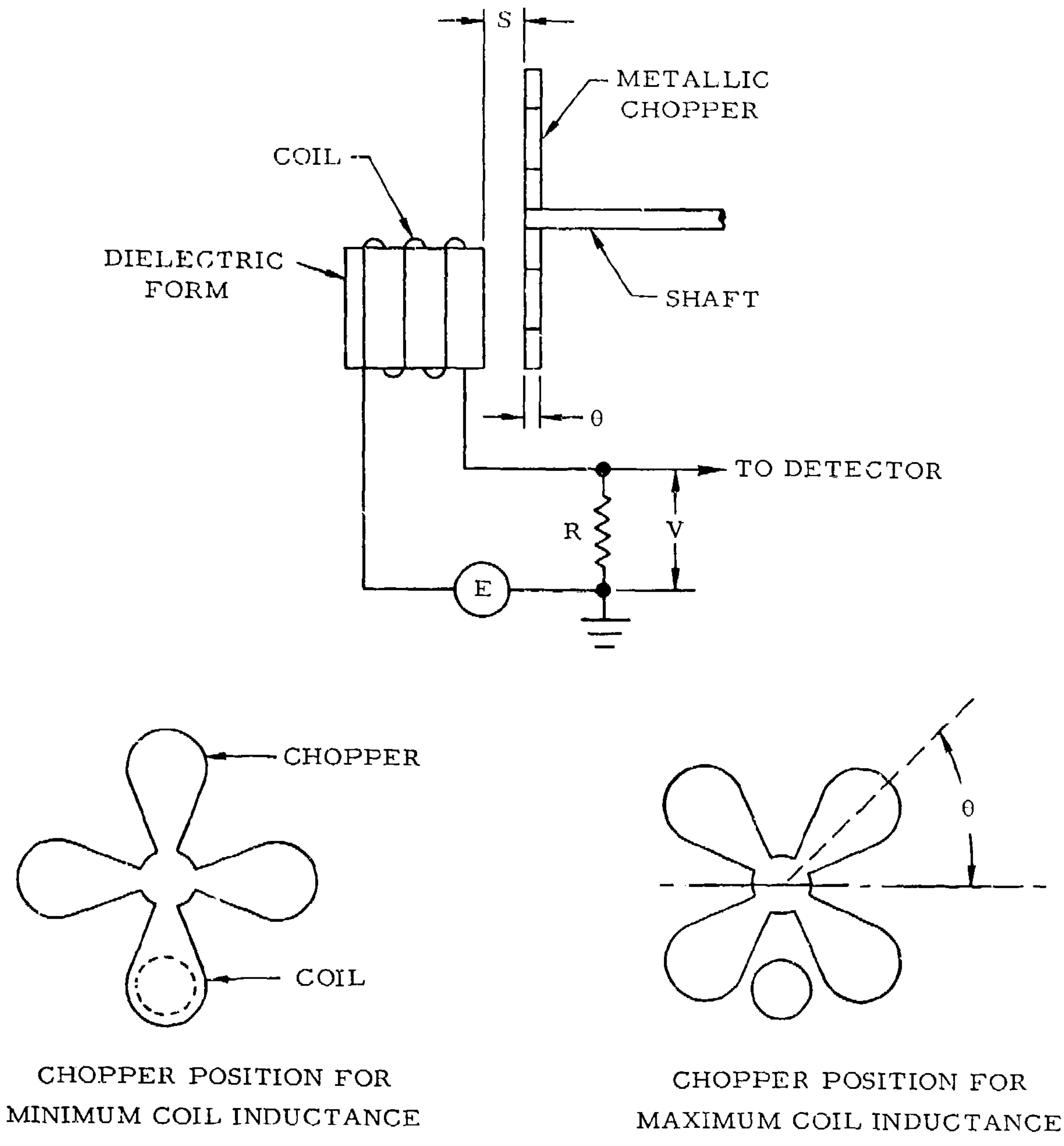

Fig. 2-84. Sketch of Simple Eddy Current Transducer

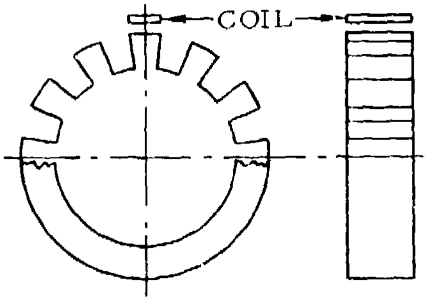

Fig. 2-85. Gear Type Structure

When a secondary coil is placed in proximity to the primary excitation coil and chopper, a mutual-inductance eddy current transducer is formed. In this case, the mutual inductance is a function of the chopper position.

A schematic diagram of an experimental circuit is shown in Figure 2-86. A bridge type detector is used in order to detect small percent changes in inductance. Both bridge arms are tuned to parallel resonance by capacitors in parallel with the coils. The bridge output is an amplitude modulated signal and 50% modulation has been obtained during experimental work (Ref. 167). Experimental results indicate that an eddy current sensor having high resolution and speed range from zero to 50, 000 rpm can be designed.

2-7 MEASUREMENT OF FUEL QUANTITY

Operational characteristics of high-performance aircraft, missiles, and rockets have created the need for accurate fuel measuring devices that can be applied to all types of fuels, tank configurations, and attitudes. Further, the environmental conditions may vary over wide ranges during flight. Fuel systems and measuring devices have been subjects of continuing studies and experimental work. Some of these techniques are discussed in the following paragraphs.

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167 Ibid., pp. 69-71.

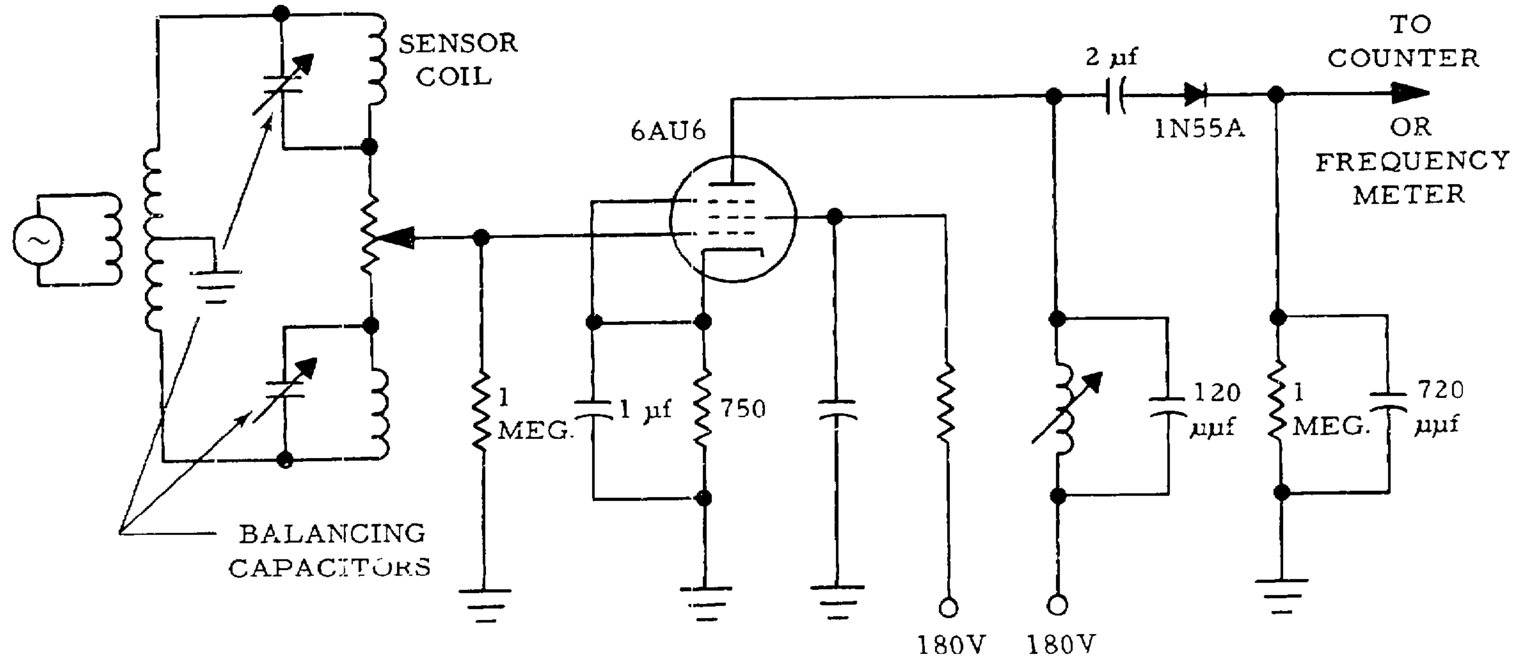

Fig. 2-86. Experimental Eddy Current Transducer Circuit

a. Optical Discrete Point Fuel Measuring System (Ref. 168)

The optical probe is based on the principle that light will be transmitted through a glass-liquid interface and will be reflected back from a glass-air interface. This principle is illustrated in Figure 2-87. Each sensor probe is made up of three basic parts as follows:

1. A light source
2. A short glass rod
3. A photosensitive element

These parts are positioned so that the light is directed into one end or surface of the glass element, and the reflections from the air-glass interface are received by the photosensitive element at the instant the fluid meniscus breaks away from the tip of the glass rod or when the liquid recovers the glass surface.

By using the proper amplification and coupling techniques, it is possible to use the output signal of the photosensitive element to modulate a telemetering subcarrier oscillator. Thus, a transmittable signal is available, by which an accurate measurement of the liquid level at a discrete point can be made.

Apparent limitations of the discrete point optical device are as follows:

1. Erroneous signals occur when sloshing fuel alternately covers and uncovers the probe.

2. The device requires a large amount of wiring, both to light sources and to the photocells.

3. The device is essentially a level indicator and is not readily adaptable to mass measurement.

4. Any coating action by the fuel on parts of the optical system may decrease the sensitivity of readings and cause erroneous readings.

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168 Lucic, A. and R. C. Beckwith, Fuel Quantity Measuring Techniques Development Study , Autonetics, a Division of North American Aviation, WADD TR 59-785, January, 1960. pp 8-18.

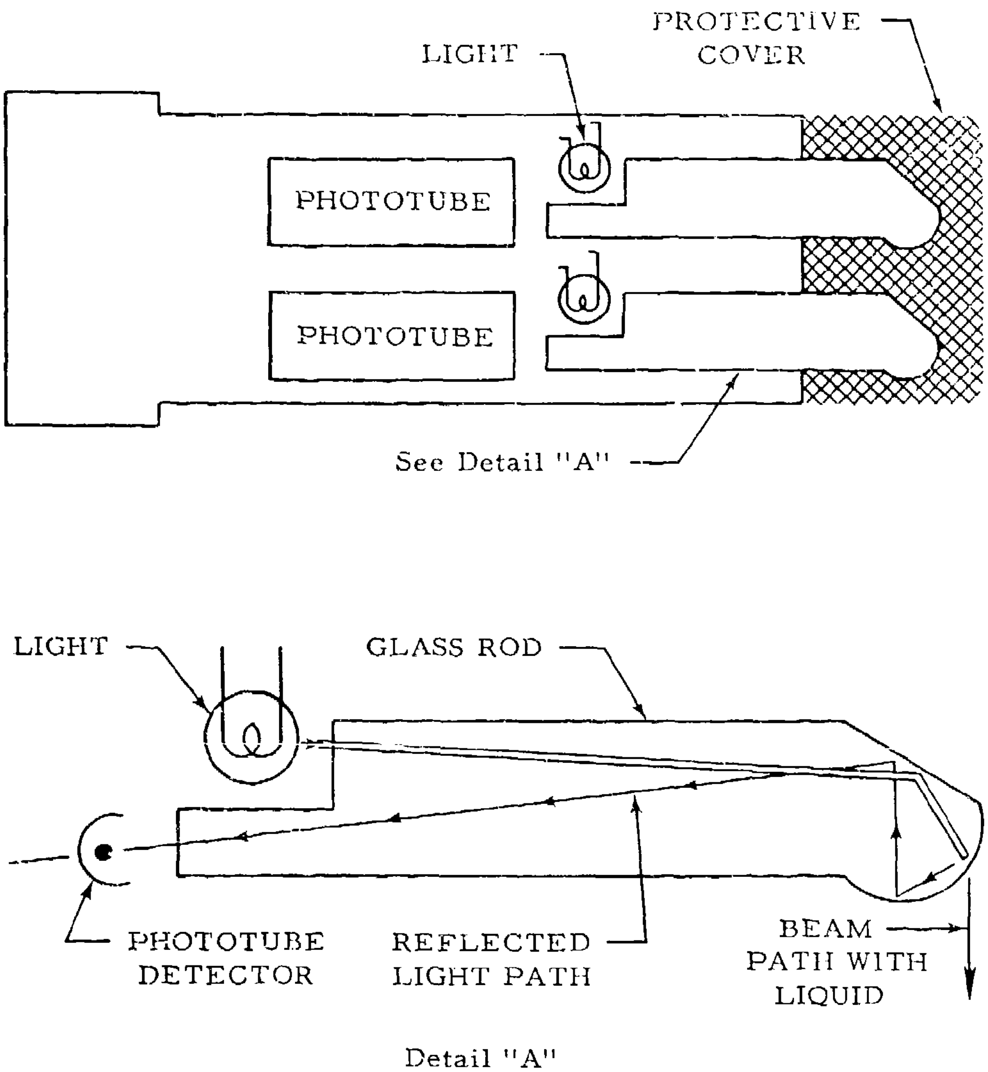

Fig. 2-87. Operating Principle of Optical Monitor System

b. Continuous Type Optical Fluid Level Sensor System (Ref. 169)

Experimental work toward the development of a continuous type optical fluid level sensor system has been carried out by Autonetics, a division of North American Aviation. The necessary characteristics of this system were defined as follows:

1. The light source must have uniform light output throughout its length, must be capable of being produced in different lengths compatible with tank dimensions, and must be contoured or contour masked to compensate for tank dissymmetries. The light source must also be capable of being fastened intimately to an optical surface and sealed to permit immersion in liquid fuels or oxidizers. Further, it must be capable of withstanding temperatures in the range of -55° to +70°C, which should be extended to -247° to +350°F to meet extreme environmental conditions.

2. The system must have good optical properties and the capability of being produced in lengths which are compatible with tank dimensions.

A continuous type optical fluid level system may consist of the following parts:

1. A 45° prism with optically ground surfaces whose length is a function of tank depth.

2. A light source capable of being intimately attached to one-half of the prism surface which is opposite its 90° angle, and whose length is also a function of tank depth.

3. A photovoltaic strip cell capable of being intimately attached to the remaining one-half of the prism surface which is opposite its 90° angle. The strip cell length is also a function of depth of the tank.

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169 Ibid., pp. 19-32.

Figure 2-88 illustrates this system wherein the prism, electroluminescent (EL) light source, and photovoltaic cell are located within the tank. Light paths are shown in Figure 2-89

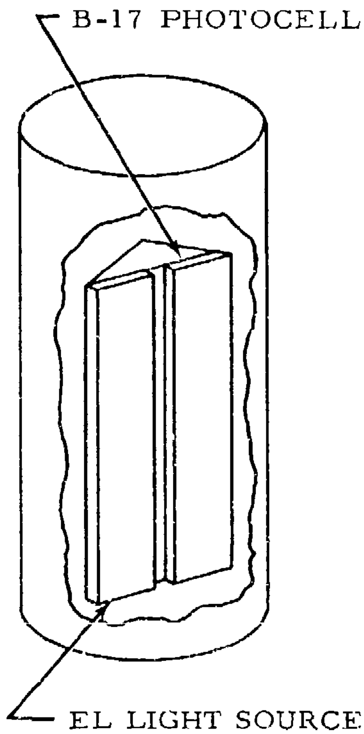

Fig. 2-88. Continuous Type Optical Fuel Level Sensing System

When the prism, light source, and photocell are immersed in a liquid whose index of refraction is near that of the prism, a large portion of the light is diffused through the liquid. However, when the prism is exposed by liquid level changes, the light is reflected internally within the prism to the photocell in accordance with the law that the "angle of incidence must equal the angle of reflection." When light passes from any medium to another in which the light velocity is greater, refraction greatly diminishes and reflection begins at a critical angle of incidence θ such that

$$\sin \theta = 1/n \qquad (2-42)$$

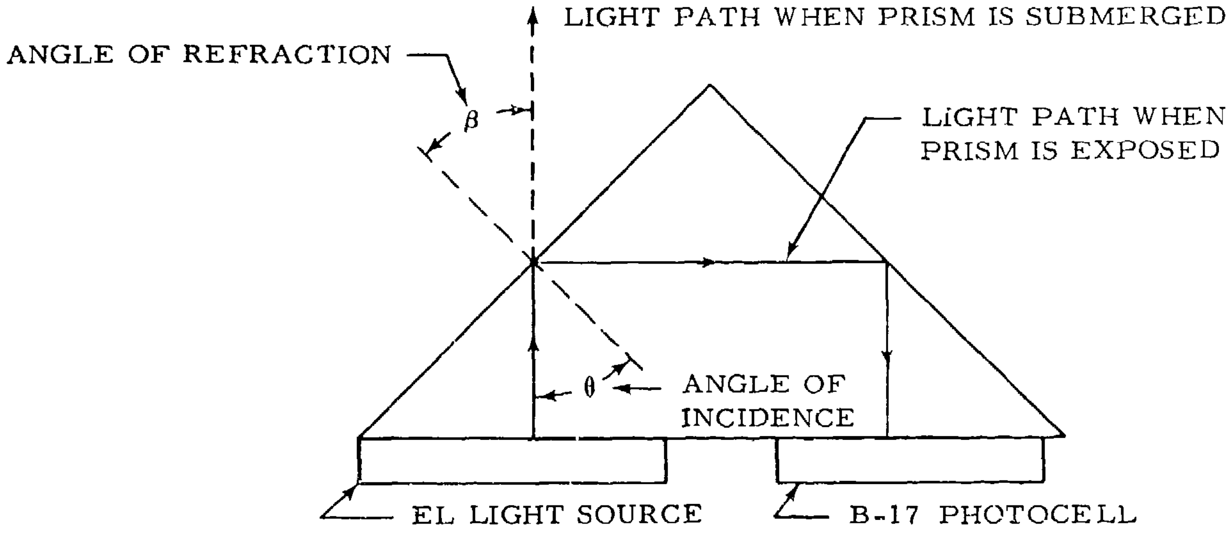

Fig. 2-89. Light Paths in Continuous Type Optical Fuel Level Sensing System

where

n = the index of the first medium with respect to the second medium

With the prism uncovered, the second medium is air, thus

$$n = n_1/n_2 \tag{2-43}$$

For zinc crown glass, $n_1 = 1.517$;

therefore

$$n = 1.517/1$$

and

$$\sin\theta = 1/1.517 = 0.662$$

$$\theta = 41°, \text{ 27 minutes}$$

If the angle of incidence is 45° and greater than the critical angle, then theoretically total reflection will occur.

When the prism is immersed in water

$$n = n_1/n_2 = 1.517/1.33 = 1.135 \qquad (2\text{-}44)$$

therefore

$$\sin 0 = 1/1.135 = 0.88$$

and

$$\theta = 61°, \ 39 \text{ minutes}$$

When the prism is immersed in benzine, $n_2 = 1.526$

$$n = 1.217/1.526 = 0.995 \qquad (2\text{-}45)$$

therefore

$$\sin \theta = 1/0.995 = 1.00$$

and

$$0 = 90°$$

In the above examples, the critical angles are larger than the angle of incidence and reflection will be very small. The incident light will pass through the prism and be diffused in the liquid. Thus, the light received at the photocell will be at a minimum when the assembly is completely immersed in the liquid.

c. Ultrasonic Discrete Point Fuel Measuring System (Ref. 170)

(1) Operating Principle

The presence or absence of a liquid at a predetermined tank level may be monitored by means of a system employing a

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170 "Ultrasonic Liquid Level Switches," Document DO 550B, Acoustica Associates, Incorporated, Los Angeles, California.

crystal oscillator circuit with the piezoelectric element positioned at the desired measuring level. The oscillator-type level switch is sometimes referred to as an ultrasonic level switch if its circuit oscillates at an ultrasonic frequency in the absence of a liquid surrounding the piezoelectric probe. A frequency of approximately eighty kilocycles is used in systems manufactured by Acoustica Associates, Incorporated.

The level switch system consits of a piezoelectric probe connected by a cable to a control unit containing the oscillator circuit and a relay. A block diagram of the basic system is shown in Figure 2-90. Incremental changes may be detected by employing several systems with probes located at various levels.

The level sensing probe is basically a piezoelectric crystal bonded to the inside of the probe tip. This crystal is a part of the oscillator resonant tank circuit and vibrates at its natural frequency when the probe is exposed to air or gas. Under this condition, the acoustic

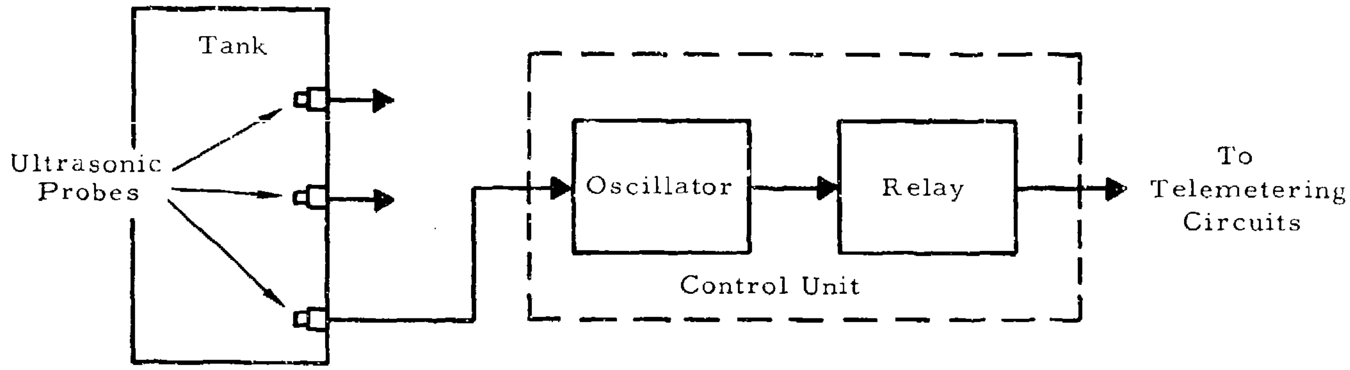

Fig. 2-90. Block Diagram of Oscillator Level Switch

impedance experienced by the crystal is relatively low, and therefore, it is free to vibrate so that continuous oscillations occur. When immersed in a liquid, the probe's acoustic impedance increases and oscillations cease because of the damping effect of the liquid. The relay is coupled to the oscillator circuit, and its contacts may open or close to provide the desired switching action when the oscillatory state changes.

Probes which are hermetically sealed and have very low input power are considered to be practically explosion-proof. They have been manufactured to operate over a large temperature range (-320° to +350°F) and are accurate to within 0.1 inch in a wide variety of liquids.

(2) Mounting

The accuracy with which level can be sensed is influenced by probe placement. As indicated in Figures 2-91, 2-92, and 2-93, they can be mounted in three basic ways: vertically, horizontally, or inverted.

The vertical mounting affords the most accurate switching. Switching action always occurs at point A (Figure 2-91) resulting in accuracies as great as ±1/64-inch. This accuracy is limited by meniscus effect, which can result in slight lags in switching during tank voiding operations.

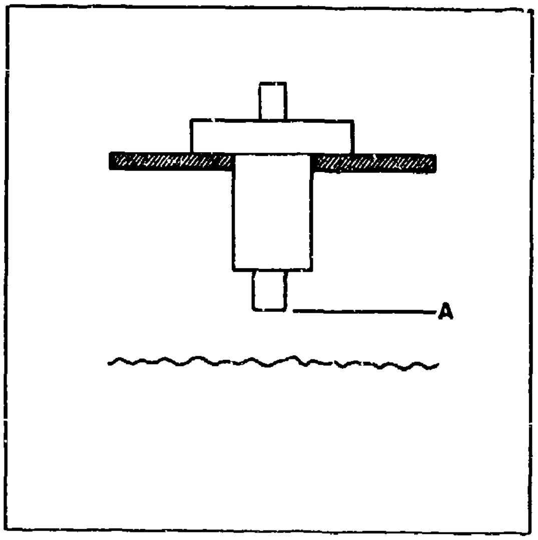

Fig. 2-91. Horizontally Mounted Probe

The horizontal mounting is used in operations that require mounting the probe through the tank wall. With this type of mounting, the switching action occurs between points B and C (Figure 2-92) which may be approximately 3/8-inch apart. The exact switching point will vary from probe to probe. With the horizontal

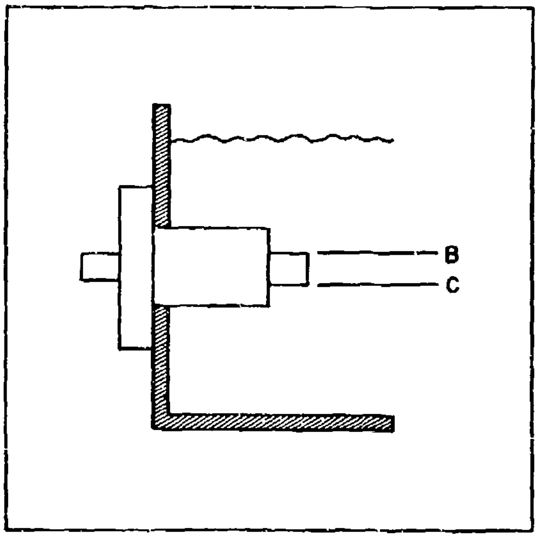

Fig. 2-92. Vertically Mounted Probe

mounting, however, the switching point on an individual probe will remain constant for both voiding and filling operations.

A probe mounted in the inverted position (such as mounting through the bottom wall of the tank) will not provide the measurement accuracy of the vertically mounted probe. Switching action will not occur exactly at point A (Figure 2-93). The effects of side-loading on the piezoelectric probe, resulting from the liquid medium around the probe between points A and D, cause variances in the switching position from one probe to another. However, as with the horizontally mounted probe, there is no variation in the switching position of an individual probe in voiding and filling operations. Switching will occur somewhere between point D and a location slightly above point A.

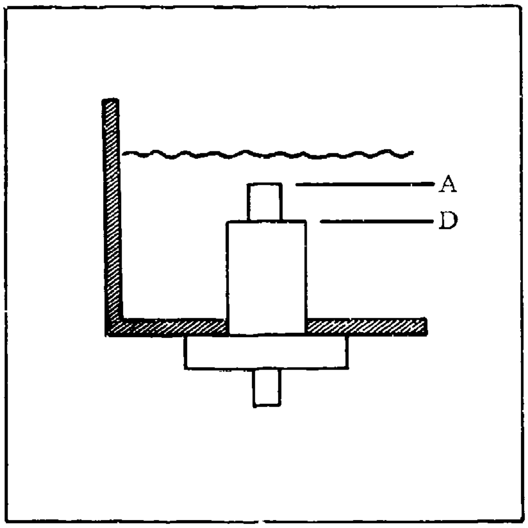

Fig. 2-93. Inverted Mounting

Regardless of the probe mounting position, care must be exercised in the design of the installation to ensure optimum performance. Air bubbles entrapped about the probe, adhesion of liquid to the sensitive surface through surface tension, sloshing, vortexing, and turbulence effects must be avoided or compensated. If air bubbles are entrapped about the sensitive surface of the probe, a dry condition could possibly be registered even when the probe is immersed in the liquid medium. The adhesion of liquid to the probe, even when the level of the liquid is below the probe, can result from locating a vertically mounted probe too close to the bottom of the vessel. The liquid, especially a liquid of high viscosity, will adhere to the probe by surface tension and will cause a wet condition to register when the probe is actually dry.

Sloshing and vortexing effects represent a problem that is not so easily overcome. Liquids splash on the sensitive surface of an otherwise dry probe and cause a momentary wet condition to be registered. To minimize this effect, stillwell assemblies may be designed for damping out turbulence. The probes can be mounted in a stillwell to maintain the true level of the liquid under severe conditions of vibration and sloshing.

d. Ultrasonic Continuous Type Liquid Level Sensing System (Ref. 171)

This system, manufactured by Acoustica Associates, Incorporated, consists of two Invar rods placed in a stillwell. Lead zirconate transducers are affixed to the top of the rods. A pulsed 100-kc square wave is applied to one rod, and the time required for the pulse to travel the length of the rod, across the liquid interface, and return through the length of the other rod, is measured. The time measurement is proportional to fuel height.

The transducers and rods are capable of operation at 350°C.

e. Gulton Industries Sonar System (Ref. 172)

An ultrasonic system developed by Gulton Industries has its transducer mounted externally on a tank at a spot that has been machined to a thickness that will prevent undue attenuation of the signal. An ultrasonic pulse generated by the transducer is reflected from the fuel-air surface back to the transducer and retriggers the pulse transmitter. The repetition rate of the pulse transmitter is a direct measure of the height of the liquid level.

Accuracy of this system during static liquid conditions is about 0.1% using digital output. In converting to analog output, the accuracy drops to about 2%. At some sacrifice to accuracy during slosh, it is possible to use a wide sonar beam up to 30° and obtain liquid level indications that would be otherwise impossible to obtain. Attitude changes above 30° will give no return signal and the system becomes inoperative.

f. Bogue Electric Company Sonar System (Ref. 173)

This system employs repetitive ultrasonic pulses to obtain true measurement of liquid height. A sinusoidal voltage pulsed at a 60-cps rate

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171 Luci, op. cit., pp. 35-36.

172 Ibid., pp. 36-39

173 Ibid., pp. 39-52

is impressed on a barium titanate transducer. In response, the transducer directs an ultrasonic pulse to the liquid-air interface. The time interval required for the pulse to round-trip the liquid path is converted to a voltage which is directly proportional to liquid height. A second transducer spaced exactly one foot from a metal reflector provides an exact calibration facility for any given temperature. Figure 2-94 shows the relative positions of the transducers and calibrating reflector plate.

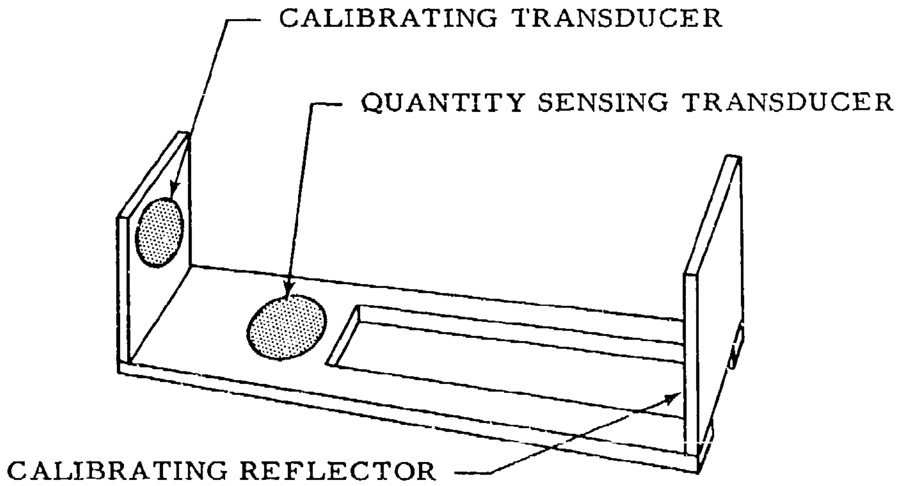

Fig. 2-94. Sonar Transducer and Reflector Assembly

g. Rocketdyne-Autonetics Sonar System (Ref. 174)

Rocketdyne and Autonetics divisions of North American Aviation have done some research in a common effort toward the application of a sonar fuel measuring system. The system operates on a sound ranging principle in which a pulse of electrical energy is converted to a pulse of sound energy by a sonar sensor.

The primary frequency of the electrical pulse is 400 kc, the pulse width is 20 microseconds, and the pulse repetition rate is 25 pulses per

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174 Ibid., pp. 52-59.

second (pps). A sonar sensor is located at or near the bottom of each propellant tank and is directed toward the propellant surface. When an electrical transmit pulse is applied to the sensor, it is converted to a sound pulse which travels through the propellant to the surface. It is then reflected back to the sensor and reconverted to an electrical pulse. For calibration purposes, a small portion of the transmit pulse is conducted over a known path length within the propellant and returned to the sensor. The transmit, calibrate echo, and surface echo pulses are used to trigger a telemetering subcarrier oscillator. The system has been used in conjunction with fuel and oxidizer tanks. In this case, the fuel and oxidizer sensors are pulsed alternately, each at the rate of 25 pps. This procedure allows the use of a common tuned receiver, telemetering subcarrier oscillator, and telemetering output for both propellant level measurements.

h. Radiation Sensor Fuel Measuring System (Ref. 175)

A radiation fuel gauge basically consists of a source of gamma radiation placed on one side of a container filled or partly filled with liquid to be measured, and a measuring cell located directly on the opposite side of the container. (See Figure 2-95). Gamma radiation is partly absorbed by the liquid and this absorption is measurable. This measure is a function of the liquid's density.

Two types of radiation emitters may be used: (1) Cs^{137} has a half life of 33 years and a low gamma radiation (0.662 MEV), and (2) Co^{60} has a half life of 5.3 years and a high energy radiation (1.17 and 1.33 MEV).

Because all the measuring components are located on the outside surface of the tank, the functioning of the radiation gauge is not affected by temperature, pressure, viscosity, abrasion, corrosion, fungi, conductive additives, flow, and agglomeration. Furthermore, since it has no moving parts, the life of the gauge is practically unlimited and maintenance requirements are practically nil.

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175 Ibid., pp. 72-166.

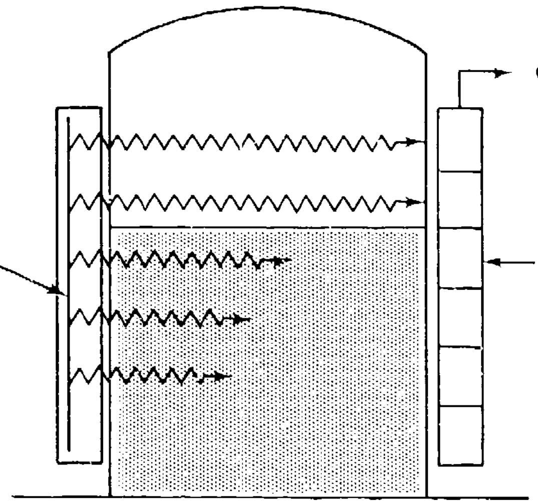

Fig. 2-95. Radiation Gauge Principle

(1) Advantages

Some of the advantages in using the radiation fuel gauge are as follows:

a. Direct application to exotic fuels and oxidizers.

b. Measures fuel mass directly, so there is no need to convert volume to mass. Mass measurement is independent of fuel temperature; therefore, temperature compensation is not necessary.

c. Reliable operation in the presence of fungus or other impurity.

d. Attitude compensation is accomplished without added weight or electronic complexity.

e. Fuel quantity measurement is independent of fuel type.

f. All components may be located externally to the fuel tank, thus providing greater simplicity in comparison to other fuel mass measuring systems.

(2) Disadvantages

Disadvantages in using the radiation fuel gauge include the following:

a. In very large fuel tanks where depth of fuel exceeds 3 feet, the choice of detector positions becomes less flexible. In most cases, it will probably be placed internally at selected locations. This procedure is necessary to control attenuation due to radiation absorption.

b. Linearization of output in complex-shaped tanks requires the use of computer techniques or in the absence of a computer, trial and error methods.

c. The system at the present state of development is inoperable in strong nuclear fields or in the Van Allen belt at 400 to 500 mi above the earth.

d. At moderate altitudes up to 100,000 feet, cosmic radiation compensating circuits may be required if currently available Geiger-Muller (GM) tubes are used as detectors. The presently used photomultiplier tube or the proposed multicellular tubes have inherent characteristics for separating cosmic ray counts from gamma ray counts.

e. The use of the photomultiplier tube at temperatures over 150°F requires additional cooling. GM tubes are proposed, however, which will operate at 350°F and will withstand 750°F.

i. SONARAD (Ref. 176)

A fuel measuring system known as SONARAD has been developed by Autonetics, a division of North American Aviation. It combines the best

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176 Ibid., pp. 167-198.

features of ultrasonic and radiation fuel quantity detection systems. In its ultimate configuration, it can always be in operation regardless of the attitude or level of the fuel in the tank. The radiation portion of SONARAD is particularly effective during slosh condition and attitudes above ±10°. The ultrasonic portion is inherently a very accurate system and is capable of measuring 0.01 inch in 24 feet. The maximum usefulness is during filling operations and during level flight conditions.

A complete description of this system and test results are given in the above listed reference.

2-8 MEASUREMENT OF AC POWER -- THE HALL WATT TRANSDUCER (Ref. 177)

a. The Hall Effect

If a conductor carries a current at right angles to a magnetic field, a charge difference is generated on the surface of the conductor in a direction which is mutually perpendicular to both the field and the current. This is known as the Hall effect which was first discovered in 1879. The development of very high mobility semiconductor compound such as indium-arsenide (InAs) and indium-antimonide (InSb) has made possible the practical application of this laboratory phenomenon. As an example, the Westinghouse Electric Corporation has designed a Hall generator consisting of a thin wafer of InAs. It is essentially a solid state multiplying element which provides an output voltage proportional to the product of two electrical quantities. Figure 2-96 illustrates the principle of the Hall effect wherein the electrical quantities are the current passing through the semiconductor and the magnetic field perpendicular to it.

The multiplying characteristics of the Hall generator are best described by the Hall equation which is as follows:

$$v_H = (R\, i_c\, B/d)\, 10^{-8} \qquad (2\text{-}46)$$

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177 Barabutes, T. and W. J. Schmidt, "Principles and Considerations in the Design of a Hall Multiplier," Paper No. CP59-875, American Institute of Electrical Engineers.

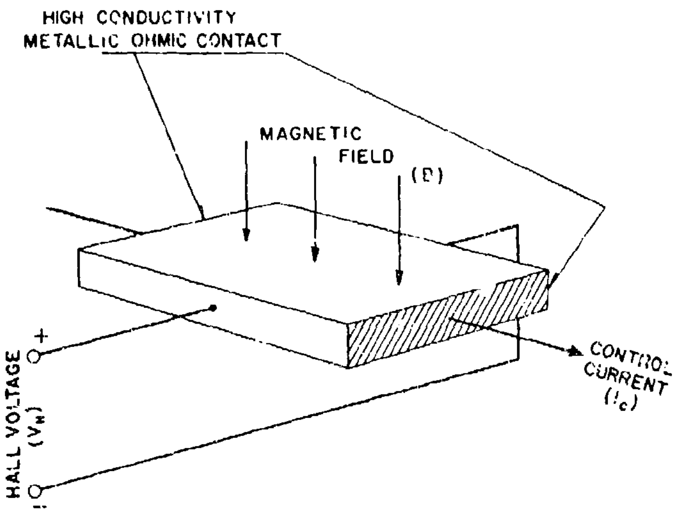

Fig. 2-96. Principle of the Hall Effect

where

v_H = instantaneous Hall voltage in volts

R = Hall constant in ohm-cm^3/coulomb

i_c = instantaneous control current in amperes

B = instantaneous flux density in gauss

d = thickness of Hall generator in cm

It is possible to have an output from the Hall generator with only control current applied. This output, called the null voltage, is due to the fabrication difficulties encountered in connecting the Hall output leads to the generator. The magnitude of this null voltage depends upon the magnitude of the control current and how closely the output leads are connected to equipotential points on opposite sides of the generator wafer.

It is possible to have an output from the Hall generator with only a field applied, if this field is varying. This voltage may be induced in the

output by flux linking the output leads. It can be minimized by making the plane of the loop, formed by the output leads, parallel to the magnetic field.

b. The Hall Multiplier

In order to make use of the Hall generator's multiplying characteristics, the generator must be placed in a magnetic field. Figure 2-97 illustrates the basic components of a Hall multiplier. The control current (i_C) is applied directly to the generator while the magnetic field and the air gap of a "C" shaped magnetic structure is produced by a current i_f.

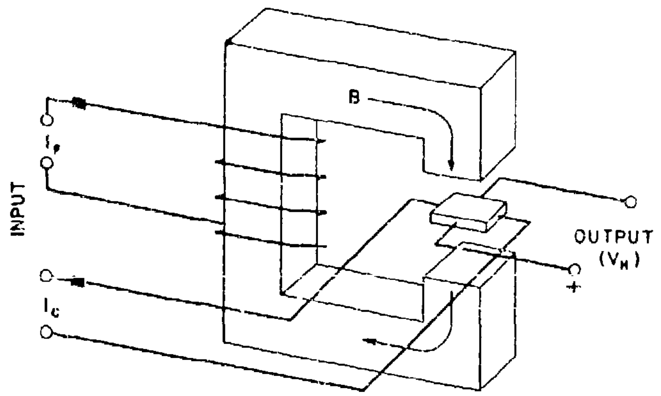

Fig. 2-97. Hall Multiplier

If the magnetic structure acts linearly, the flux density in the air gap will be given by

$$B = K_1 i_f \tag{2-47}$$

where

K_1 = constant of proportionality depending on the design of the magnetic structure in gauss/ampere.

i_f = instantaneous field current in am, ·es.

Substituting equation (2-47) in equation (2-46) yields

$$v = K_2\, i_f\, i_c \qquad (2\text{-}48)$$

where

$K_2 = (K_1\, R/d)\, 10^{-8}$; a constant depending upon the parameters used in the design of the various elements.

The development of equation (2-48) shows that the device illustrated in Figure 2-97 will produce an output voltage proportional to the product of two input currents.

c. The Hall Watt Transducer

An ideal application for the Hall multiplier is the measurement of ac power. Figure 2-98 shows how the multiplier is connected to perform this measurement. The field is energized by the current in the

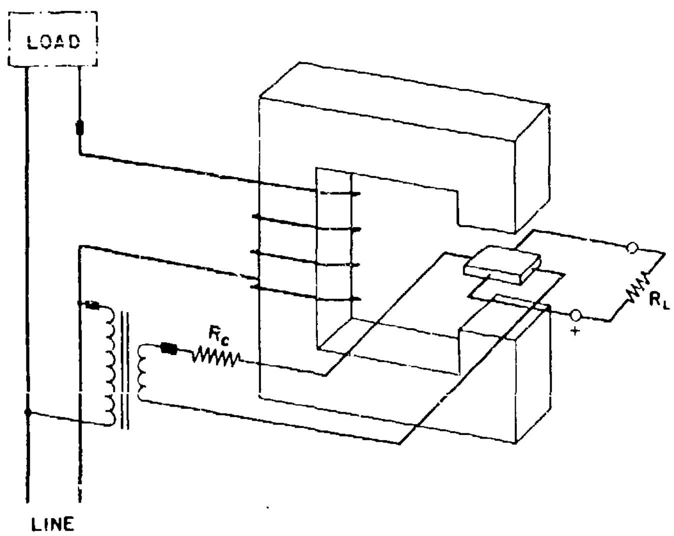

Fig. 2-98. Hall Watt Transducer

line, and the control circuit is energized by the line voltage. The resultant output from the transducer is proportional to the power being delivered by the ac circuit. The Hall Watt Transducer shown in Figure 2-98 is connected to measure single phase power. To extend its application to polyphase power measurements, two or more such devices may be used with their Hall outputs connected in series.

The above described conditions may be expressed mathematically by equation (2-49) which states that the field current is proportional to the line current, and by equation (2-50) which states that the control current is proportional to the line voltage.

$$i_f = K_3\, i_L \tag{2-49}$$

$$i_c = K_4\, e_L \tag{2-50}$$

where

i_L = instantaneous line current in amperes

e_L = instantaneous line voltage in volts

K_3 = constant of proportionality between i_f and i_L

K_4 = constant of proportionality between i_c and e_L

Substituting equations (2-49) and (2-50) in equation (2-48) results in

$$v_H = K_2\, K_3\, K_4\, i_L\, e_L \tag{2-51}$$

It may be assumed that the line voltage and current are given by

$$i_L = I_{max} \sin (\omega t + \theta) \tag{2-52}$$

and

$$e_L = E_{max} \sin \omega t \tag{2-53}$$

Substituting (2-52) and (2-53) in equation (2-51) gives

$$v_H = K_2\, K_3\, K_4\, I_m\, E_m \sin (\omega t + \theta) \sin \omega t \tag{2-54}$$

By expansion of equation (2-54) it is seen that

$$v_H = K_2 K_3 K_4 (I_m E_m /2) \quad \left[\cos \theta - \cos (2\omega t + \theta)\right] \quad (2\text{-}55)$$

Since the frequency response of the Hall generator is in the order of one megacycle, the output will follow the instantaneous power wave which is expressed mathematically by equation (2-55). Inspection of this equation shows that the transducer output contains dc and ac components. The dc term, $(I_m E_m /2) \cos \theta$, is proportional to the true power in the ac circuit and is, therefore, a measure of this power.

2-9 MEASUREMENT OF ACCELERATION (Ref. 178)

Acceleration is the rate of change in velocity. Most acceleration measurements are made to determine the forces involved, which can be computed, since $F = ma$. If deflection is the quantity required, as in vibrations. the measured acceleration can be integrated twice to obtain it.

There are two general types of accelerometers, linear and angular. A linear accelerometer is a mass which is free to move in one direction only and against a restraining spring. If the free period of oscillation of the accelerometer is less than that of the acceleration, the deflection of the spring is proportional to acceleration. The free period of the accelerometer decreases as the mass is reduced or the spring stiffened, either of which results in a decrease in sensitivity. The sensitivity is defined as the deflection of the spring per unit acceleration. To measure accelerations occuring in shorter time intervals greater sensitivity in measuring deflections is required.

In angular accelerometers a symmetrical mass in the form of a disk is mounted so that it may deflect about its center of gravity. The angular deflection, restrained by a spiral spring, is proportional to angular acceleration. The angular deflection, which is kept small by choice of spring stiffness and the moment of inertia of the mass, is detected by an electric pickup, such as a differential transformer an E-type inductance pickup, or an electric resistance. Liquid damping is usually used. Response to rapidly imposed accelerations can be secured only by decreasing the period of oscillation, thus decreasing the sensitivity.

Figure 2-99 (Ref. 179) shows a schematic of a fundamental linear accelerometer in which a mass is suspended from the accelerometer case by

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178 Mc-Graw-Hill Encylopedia of Science & Technology, Vol. 1, p. 27 & 28

179 Eugene B. Canfield, "Accelerometers and Their Characteristics," Ordance Dept., General Electric Co., Pittsfield, Mass.

means of a spring. Damping is accomplished by either mechanical or electrical means and the case is mounted rigidly to the device whose acceleration is desired. The relationship between acceleration of the case and motion of the mass can easily be developed. See Appendix IV for detailed derivation. Assuming the accelerometer damping constant is close to unity, the accelerometer will give an indication of acceleration if moved at frequencies from zero to approximately the resonant frequency. At excitation frequencies above resonance, the output no longer is proportional to acceleration.

The diagram in Fig. 2-100 shows an adaptation of the basic accelerometer of Fig. 2-99 to a problem requiring relatively low accuracy. The mass is supported on a rod and restrained at either end by slightly compressed springs. Damping may be accomplished pneumatically or by means of oil flowing through the small clearance between the mass and the case. Output is available from a potentiometer pickoff. The advantages of this class instrument are:

1) low cost
2) simplicity and reliability
3) freedom from cross talk

The disadvantages are:

1) poor threshold level due to friction
2) poor resolution due to type of pickoff
3) poor repeatability due to hysteresis in spring plus friction effects
4) low resonant frequency (in order to provide maximum travel of mass).

A more sophisticated version of the same type of accelerometer is shown schematically as Fig. 2-101. Here the mass is surrounded by oil or other fluid to give damping. The oil may also act to reduce friction. A stiff magnetic or possibly hydraulic suspension may be used to keep friction to a minimum and prevent the mass from rubbing the guide rod in some applications. Unfortunately, in order to accomplished this, the suspension means must be very stiff if the instrument is subjected to large accelerations along axes other than the sensitive axis. Instead of a mechanical spring, an electrical spring is used to restrain the mass. The electrical spring is made up of a pickoff such as the E-type shown, an electronic amplifier and a linear motor. Since the motor produces force on the mass as a function of its current, the current into the motor is directly proportional to acceleration. Accelerometer output is usually taken as a voltage across a resistor in series with the motor winding.

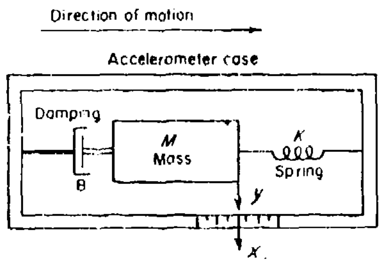

Fig. 2-99 Fundamental linear accelerometer.

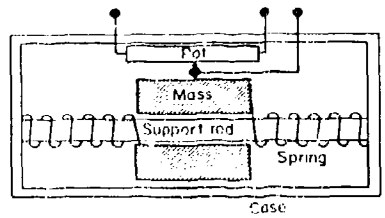

Fig. 2-100 Adaptation of basic unit shown in Fig. 2-99 for relatively low accuracy use.

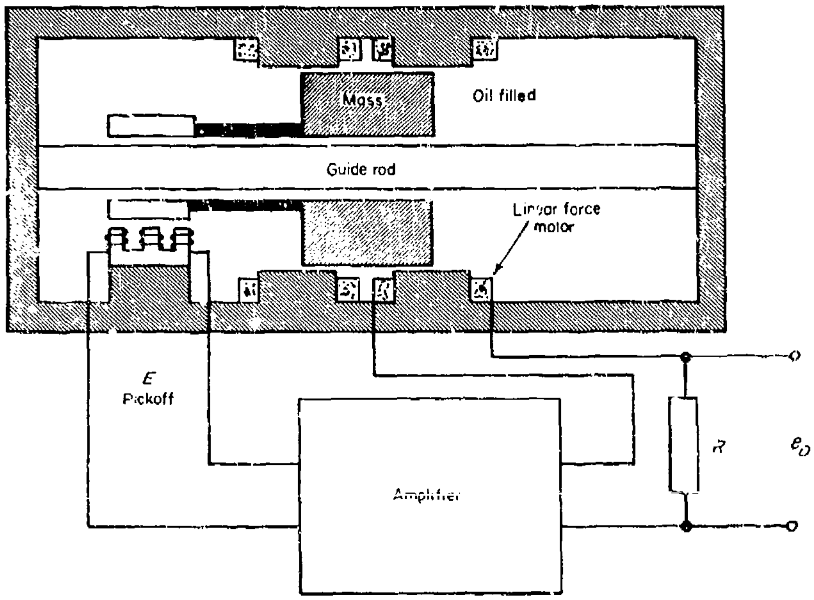

Fig. 2-101 Accelerometer with mass floated in oil to minimize friction and prevent mass from being forced against guide rod by accelerations along axes other than the sensitive one.

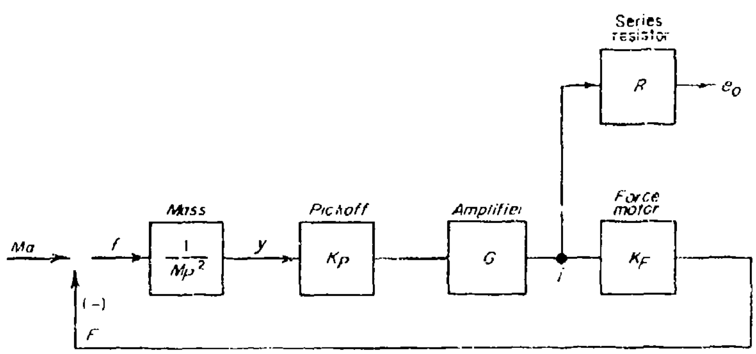

Fig. 2-102 Block diagram of accelerometer shown in Fig. 2-101.

Equations relating the motion of this device are presented in the Appendix IV. The advantages of this type of instrument are:

1) high resonant frequency possible
2) hysteresis effects eliminated, excellent repeatability
3) low threshold level
4) good resolution and sensitivity to small changes in acceleration
5) freedom from cross talk

This device is more complex and costly than the simple instrument of Fig. 2-100. Unfortunately, the mass cannot be floated to neutral buoyancy as in the pendulous accelerometer, and adequately stiff suspensions often are not practical. Therefore, the friction deadband level may run higher than in the floated, magnetically suspended pendulous accelerometer. Absolutely accuracy of this accelerometer is dependent upon the linearity of the force motor, the stability of the output resistor, and the friction deadband.

An accelerometer of intermediate quality between that of Fig. 2-100 and 2-101 is shown by block diagram in Fig. 2-102. The schematic is as in Fig. 2-101 but the mass is not suspended or damped. Cost is reduced at sacrifice of threshold level and resolution and lack of damping must be compensated for in the electronic amplifier. The equations for this type accelerometer are given in the Appendix IV.

Another class of accelerometers is represented by the pendulous type shown in Fig. 2-103.

In this instrument a pendulum is suspended on an axis so that it is free to move through an angle with respect to the accelerometer case. Damping again is accomplished by either mechanical or electrical means and the pendulum is restrained by a torsion spring. See Appendix IV for derivation of equation.

In actual practice, the pendulum is of the compound type shown in Fig. 2-104. This type is broken down into two components: a mass whose center of gravity is concentric with the axis of rotation, 0, and a small mass on the periphery of the pendulum. This small mass provided the unbalance of the compound pendulum and is assumed to be concentrated at a point. Thus, this unbalanced mass is assumed to act in exactly the same way as the mass of a simple pendulum. The force of linear acceleration of this mass, when multiplied by the radius arm, becomes a torque which attempts to accelerate the balanced mass about the point of suspension. The acceleration of the balanced

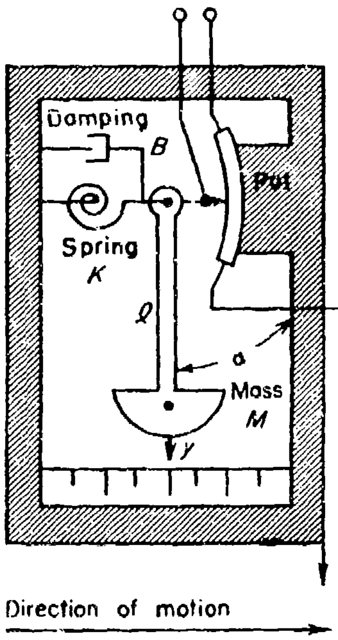

Fig. 2-103 Pendulous accelerometer.

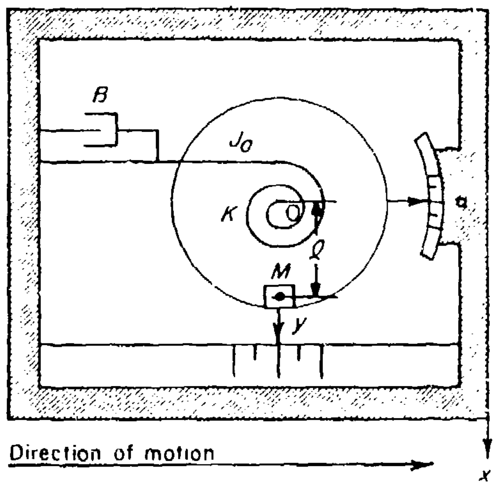

Fig. 2-104 Accelerometer with compound pendulum.

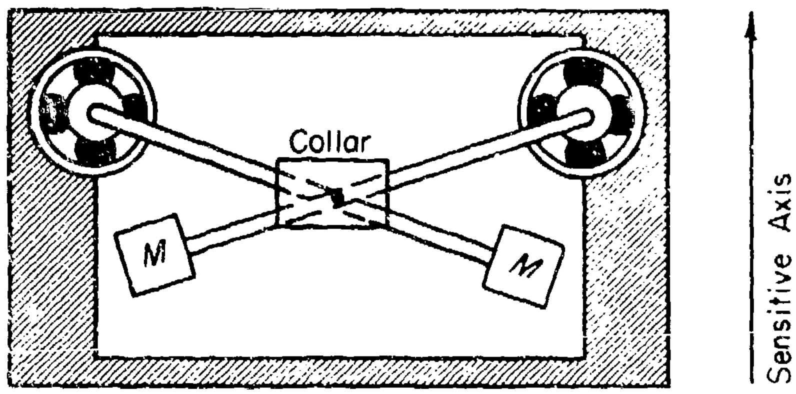

Fig. 2-105 Two simple pendulums fastened together by a collard to reduce crosstalk and maintain low resonant frequencies.

mass is resisted by its own inertia, the damping and the spring constant.

Pendulous-type accelerometers are generally chosen because they transfer linear force into an angular rotation. A great many devices have been developed for sensing angular motions or producing torques about an axis of rotation. In its simplest form, where a spring or torsion wire is used for restraint and a potentiometer becomes the pickoff, the advantages and disadvantages are about the same as for the non-pendulous accelerometer of Fig. 2-100. However, there is one notable exception: pendulous accelerometer are subject to cross talk. The slightest rotation of the pendulum due to acceleration in the sensitive direction permits the accelerometer to acquire sensitivity to acceleration in other directions of motion. Therefore, resonant frequencies of pendulous accelerometers must be kept high in order to reduce the cross talk as much as possible.

One design technique sometimes used to reduce cross talk and still maintain low resonant frequencies is shown in Fig. 2-105. Two simple pendulums are mounted in a single case and are free to rotate in the ball bearings or other support. The stiff arm of each pendulum passes through a collar which is free to slide along each arm. Rotation of the arms is also permitted inside the collar so that the motion of the arms is not impeded. However, the forces acting between the pendulum prevent the motion of either pendulum except from acceleration along the sensitive axis. Pickoff may be a potentiometer or other transducer sensing the angular rotation of either pendulum, or the linear displacement of the collar which moves in the direction of the sensitive axis.

Manufacturers of high-quality, floated, single-axis gyros have one of the best reasons for developing a pendulous accelerometer. Inside the gyro case, ready for use, is a floated, damped gimbal with a torque motor on one end and a signal generator on the other end. The gimbal carries the gyro wheel. It is quite expedient to replace the gyro wheel with an unbalanced mass to produce one of the highest quality pendulous accelerometers. An amplifier is connected between the signal generator and torque motor. Cross talk is minimized by high amplifier gain, causing high resonant frequency. Output voltage is usually obtained across a resistor in series with the torque motor much the same as shown in Fig. 2-101.

Piezoelectric accelerometers are still another class of instrument in wide use today. In these devices, the piezoelectric crystal becomes the spring restraint and converts a portion of the mechanical energy into electric energy. While having excellent characteristics out to very high resonant

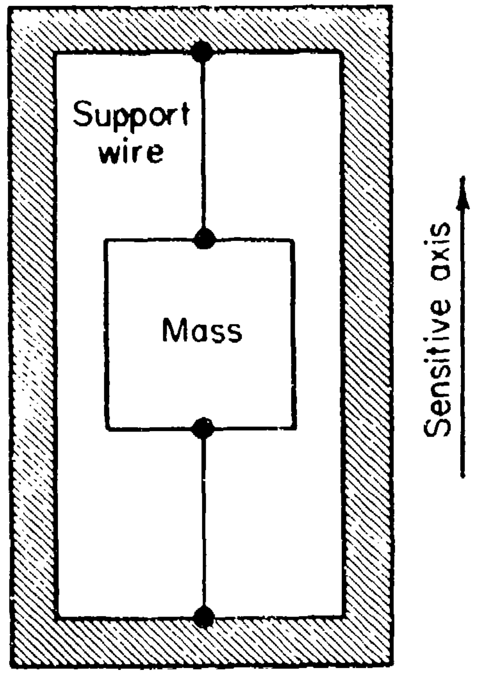

Fig. 2-106 Accelerometer with mass supported by two wires in tension.

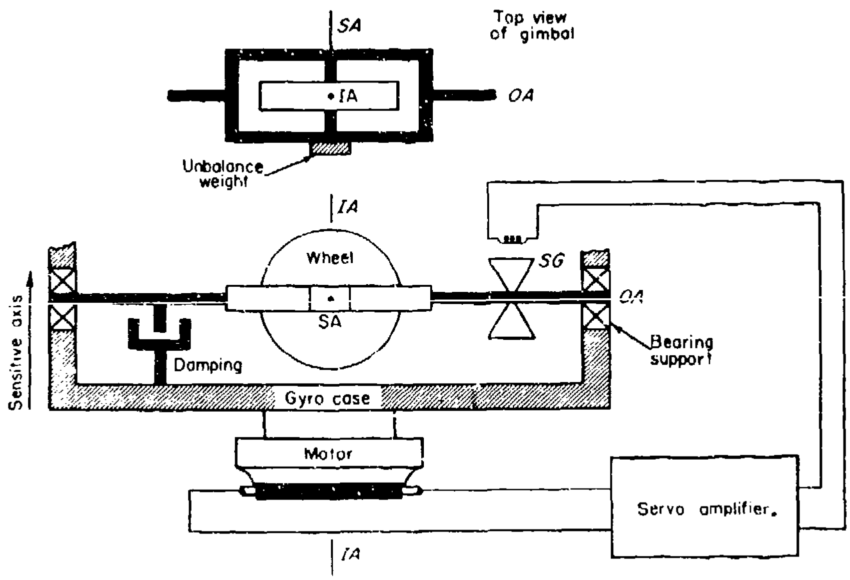

Fig. 2-107 Highly accurate pendulous gyro accelerometer including servo.

frequencies, output under steady-state constant accelerations is unfortunately not available and the devices have little use in inertial guidance. However, they make vibration pickoffs of the highest quanlity with extremely small size and they are widely used in evaluation during missile-system development.

Another accelerometer configuration is shown in Fig. 2-106 where a mass is supported by two wires in tension. Damping again is provided by electrical or mechanical means. As the case is accelerated along its sensitive axis in the direction of the arrow, the tension in the upper support wire is increased, while that in the lower wire is decreased. If a strain pickoff is associated with each wire, the sum of the output of the two pickoffs is proportional to acceleration. The device is insensitive to cross-axis acceleration because the tension of each wire is changed by an equal amount.

In another type of accelerometer, the support wires are made to vibrate at their natural frequency. As the tension of one wire increases, its natural frequency increases while the decreased tension in the other wire reduces the natural frequency. A comparison of the natural frequency of the two wires by the magnetic pickoff or other means leads to an output proportional to acceleration.

The pendulous gyro accelerometer of Fig. 2-107 represents one of the more complex (although highly accurate) devices that may be used. It consists of the conventional single-axis, floated, damped HIG gyro modified so that the gyro gimbal is unbalanced by a known amount. A servo amplifier accepts the error from the gyro signal generator and, by means of a servo motor, drives the gyro about its input axis to null the signal generator output. See Appendix IV for further details.

2-10 TEMPERATURE MEASUREMENTS

a. Introduction (Ref. 180)

Heat is a form of energy and temperature is a measure of its level. All materials that we know today have the characteristics which change with temperature. Chemical reaction, motion, pressure, stress, ionization and light show important effects related to pressure. The methods for measurement of temperature may be grouped into categories depending on the physical principles involved. One group would contain devices that function by coming to thermal equilibrium with the substance whose temperature is being measured. A second group would function in relation to the laws of radiation, and immersion or contact with measured material may not be necessary. A third group would

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180 J. C. Hedge, W. J. H. Murphy, H. J. Nielsen, J. A. Granath, H. Zucker, Armour Research Foundation, Temperature Measuring Techniques, WADD TR 60-487, Volume 1, June 1960. AD 253483

comprize miscellaneous methods for specific temperature measurement problems such as high gas temperatures, where deliberately cooled probes are used and temperature of gas calculated using laws of heat transfer or thermodynamics.

b. Thermal Equilibrium Category

The largest and most common category of measurement devices fall under this group. Some physical property of the probe which is accurately known as a function of temperature is used to determine the temperature of the material in which it is immersed. Physical properties used with these devices are: thermal expansion, vapor pressure, electrical resistance, thermal emf, thermionic emission, magnetic susceptibility, and thermal noise. Pyrometric cones and temperature indicating paints, crayons, and metals are also included in the thermal equilibrium category serving to indicate if a certain temperature has been exceeded.

When using the methods in this group, care must be exercised to insure that the probe actually does come to the temperature of the material in which it is immersed. Thermal conduction can sometimes cause the probe to assume a different temperature. Radiation losses and stagnation heating also lead to errors when probes are used to measure the temperature of gases. In many cases these errors cannot be eliminated completely and a correction calculated from the laws of heat transfer must be applied to the temperature indicated by the probe.

(1) The linear expansion of solids due to a temperature change can be used for a temperature indication and application of this principle in a temperature sensing unit is thermostatic metal, commonly called bimetal. Bimetals form the primary element in many devices that indicate and control temperature.

The action of a bimetal depends upon two metals that are bonded together having different mean thermal linear expansions. The bonding of the two metals has been accomplished by casting, riveting, soldering, brazing, or welding. The method of bonding is important, since a uniformly good and strong bond is necessary to resist the high shearing stresses when the metal is heated and cooled. The component metals are quite often bonded together in the form of two plates, this is reduced to a thin sheet by rolling. It is then cut and formed to shape. The bimetallic strip is straight at the particular temperature where their lengths are identical. When the temperature is altered one metal will expand or contract at a different rate than the other

and cause the strip to curl. By holding one end of the strip in a fixed position, the displacement of the opposite end can, after calibration, be used to indicate temperature.

Bimetals are formed into the following configurations: helical coils, spiral coils, disks and strips. These may be used under conditions of: free deflection (little force involved), restrained force or torque (little deflection involved), and combined deflection and force.

The majority of bimetal temperature indicators use the spiral or helical coil operating under free deflection conditions. The angular rotation of a pointer at the end of a spiral or helical coil under free deflection conditions may be calculated by the use of the formula;

$$A = \frac{C_1 (T_2 - T_1)\ e}{t} \qquad (2\text{-}56)$$

where

A = angular deflection in degrees
C_1 = deflection constant for coils
T_1 = temperature before deflection
T_2 = temperature after deflection
e = active length of coil
t = thickness of strip

Thus angular deflection changes inversely as the thickness of the material and directly with the deflection factor for the strip, the active strip length, and the temperature change. Values of C_1 may be found in the manufacturer's catalogs for a particular material and temperature range.

The bimetal thermometers are self-contained instruments requiring no external power. They usually contain three components: the bimetal, the indicator, and a connecting mechanism. Since they are mechanical devices, the pointer can carry contacts, min-max hands or can position a small telemetering transmitter.

(2) Liquid Expansion Thermometers

The volumetric expansion of liquids and solids can be used to indicate temperature. A relatively large quantity of liquid is held in a bulb to which a capillary tube is attached. If the liquid and bulb have different coefficients of expansion, then the change in position of the liquid column in the capillary tube may be measured and calibrated to indicate temperature.

There are two principal types of liquid expansion thermometers. One of them is the liquid-in-glass thermometer; the other is called a liquid filled thermometer.

The liquid-in-glass thermometer is probably the most common of all thermometers. It consists of a glass bulb filled with a liquid, usually mercury, and a glass capillary tube attached to the bulb. Mercury has several properties which make it desirable for use in a good grade liquid-in-glass thermometers. It has a large and fairly uniform volumetric coefficient of expansion, its low freezing point -40°C and high boiling point 356°C make it usable over a wide temperature range. This range can be extended by increasing the internal pressure which increases the boiling point of mercury. Other liquids used are toluene, alcohol, and pentane; the latter having a freezing point of -200°C.

The second type of liquid expansion thermometer consists of a metal bulb and capillary tube which is usually attached to a bourdon tube or bellows. The system is filled with a suitable liquid for the temperature range required. As the temperature of the bulb changes, pressure or volume of the liquid changes and this change is noted by the change in position of the bourdon tube or bellows. The system can be calibrated to indicate temperature.

(3) Gas Thermometers

Gas thermometry is based on the fact that for ideal gases, the pressure and volume vary with temperature according to the law:

$$PV = nRT \tag{2-57}$$

where P is the absolute pressure, V is the volume, n is the number of mols of gas, R is the universal gas constant, and T is the absolute temperature. Many gases approach the ideal gas and for gases such hydrogen, helium, nitrogen, argon, oxygen, and others it is possible to measure the deviations from ideal gas behavior so that a PVT-equation can be obtained to an accuracy of better than 0.1%. Temperature can be accurately determined with either the constant volume gas thermometer or the constant pressure gas thermometer.

A typical gas thermometer consists of a bulb containing gas, a pressure measuring device, and a capillary tube connecting the tube. For laboratory use, a simple nercury manometer is used to measure pressure. In industrial uses the pressure is usually measured with a bourdon tube gage, although other types of pressure transducers can be used.

The constant volume gas thermometer is simple, self contained, inexpensive, rugged, accurate and has a vast response. It is subject to errors caused by the fact that as the temperature rises, thermal expansion and increased pressure slightly increse the bulb volume and, secondly, increased pressure cause more gas to flow into the capillary and bourdon tube. The development of gas thermometers for measurement of high temperature presents difficulties due to the need for rigid, gas type container. At high temperatures, it is difficult to find bulb materials which will confine the gas without gradual loss by diffusion of gas through the bulb walls.

There are two forms of the constant pressure type gas thermometer. One form consists of a definite mass of gas enclosed in a bulb of variable volume at constant pressure. The second form, a definite mass of gas is enclosed in a bulb of fixed volume. Equipment for use with the constant pressure gas thermometer is similar to that used with constant volume gas thermometer except the change in volume of the gas in the bulb is measured. The constant gas thermometer is less convenient to use than the constant volume gas thermometer. For this reason, as well as the fact that it has an accuracy comparable with the constant volume gas thermometer, it has seldom been used.

(4) Vapor-Pressure thermometers make use of the pressure exerted by saturated vapor in equilibrium with a volatile liquid. This fact can be used to measure temperature if the relationship between temperature and vapor pressure of the material is known. A simple expression for relating the vapor pressure and temperature of some materials is given by:

$$\log P = A + B/T \qquad (2\text{-}58)$$

where A and B are constants. Additional terms in the equation are required to adequately represent many liquids. It can be seen from the above equation that if B is large, then small changes in temperature will cause large variations in the vapor pressure.

Vapor-pressure thermometers, like gas thermometers, are usually connected to a bourdon tube gage or similar type of pressure measuring instruments. The principal advantage of vapor-pressure thermometers is the large change in pressure for small temperature changes, which results in high sensitivity. Also, the bulb size can be made much smaller than those required for gas thermometers. The disadvantage of the method is the relatively small

temperature range over which any particular liquid can be used, although various liquids can be used to cover different portions of the temperature range above. Extention of the method to higher temperatures is limited by the availability of suitable liquids.

(5) Temperature Indicators

Among the temperature indicating types are pyrometric cones, sometimes called Seger cones. These are slender pyramids of triangular cross section made from mixtures of clay, felspar, whiting, flint, and fluxes. When subjected to high temperatures the cones soften the deform, the upper end of the pyramid curls over to form an arc until finally the tip touches the mounting surface. When a pyrometric cone is heated at a definite rate it "goes down", i.e., its tip touches the base at a definite temperature. If the heating rate is more rapid, the cone "goes down" at a somewhat higher temperature. Hence, the cone does not measure temperature, but rather the dumulative effect of time, temperature, and atmosphere. Each cone when heated in air at a prescribed rate will go down at or within a few degrees of a given temperature. The size of the cone also has a bearing on the deformation temperature. Small cones have higher deformation temperature than large cones of the same composition.

Another type temperature indicator are bars of ceramic material (Hold Craft Bars) mounted horizontally and supported at their ends, and are somewhat similar to pyrometric cones. Bars are supplied with different softening points. As the temperature is raised, some of the bars soften and sag under the influence of gravity. The temperature is indicated by the bar which just begins to sag.

Still another group of ceramic temperature indicators operate on the principle of progressive shrinkage of certain ceramic formulations as they are subjected to higher and higher temperatures (Watkins disks and Buller rings). After removal from the furnace, the diameter of a hole in the specimen or the outside diameter, is measured. The shrinkage serves as a measure of the combined effect of the temperature reached and the duration of exposure. Additional temperature indicating devices are pellets, liquids, lacquers, and crayons. They consist of mixtures of minerals havins definite melting temperatures ranging from 40°C to 1480°C. The melting temperatures correspond to the particular numbers in the series and are indicated by the advert of a wet or molten appearance. The various temperature sensitive indicators are sprayed, brushed or placed on the part whose temperature is to be measured. Visual observation during heating will allow a rough temperature

measurement, or an inspection after heating will allow the determination of the maximum temperature achieved within the limits of the indicators used.

(6) Resistance Thermometers

The operation of a resistance thermometer is based on the fact that the electrical resistance of materials varies with temperature. The resistivity of most metals increases with increased temperature. The resistivity of electrolytes, semiconductors, and insulators decreases with increased temperature. The main factor causing the rise in resistivity is the increased inner action of electrons with atoms that are displaced from their positions in the metal lattice, resulting in a short "mean free path" for the electrons. First use of the resistance principle is credited to Siemens in 1871. This thermometer was constructed of platinum wire. However, unfavorable results were obtained with it due to his choice of material for mounting the platinum wire. Callendar, in 1887, devised a superior platinum resistance thermometer and is credited with laying the foundation for modern resistance thermometers.

A resistance thermometer system consists of a resistor mounted on a suitable frame, a resistance measuring instrument, and connecting leads between the two. The resistance measuring instrument is usually a Wheatstone bridge or a potentiometer.

Since the resistance element is usually at a remote location from the measuring instrument, the connecting wires are usually subjected to various changing temperatures along their length. This results in a variation in their resistance which must be eliminated if the system is to be accurate. Three types of connections have been devised to overcome this difficulty. These are shown in Fig. 2-108.

The Siemens three-lead method of compensation, Fig. 2-108a, is shown connected to a Wheatstone bridge in Fig. 2-109. When the Wheatstone bridge is balanced so that the galvanometer G does not deflect,

$$\text{then } R + C/r_1 = X + T/r_2 \qquad (2\text{-}59)$$

The lead wires of the resistance element T and C are made to have equal resistance. The ratio arms r_1 and r_2 are set so that $r_1 = r_2$. Then by the above equation, R = X. Thus the measured resistance is of the resistor only, since the lead resistance is eliminated.

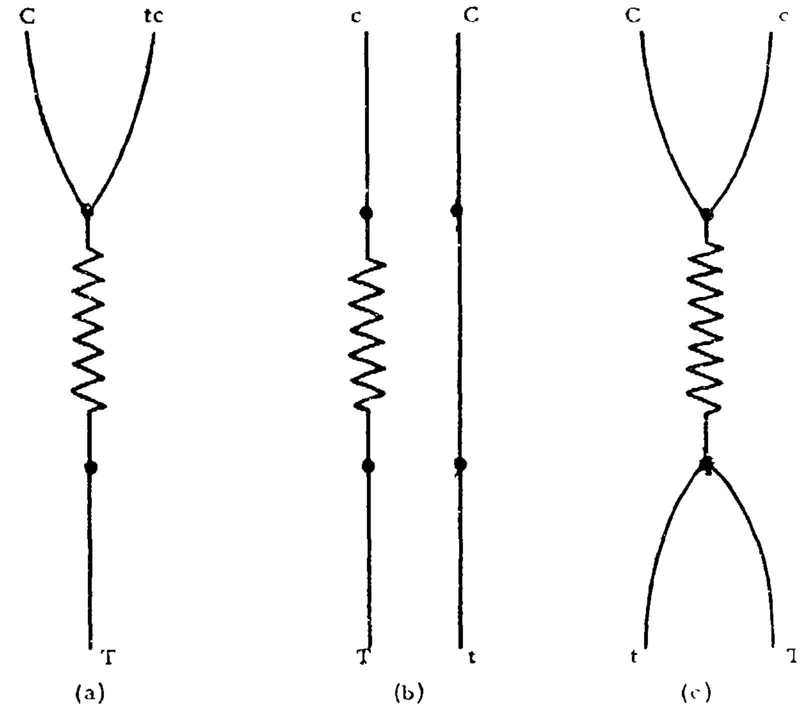

Fig. 2-108 Three Types of Connections Used in Resistance Thermometers

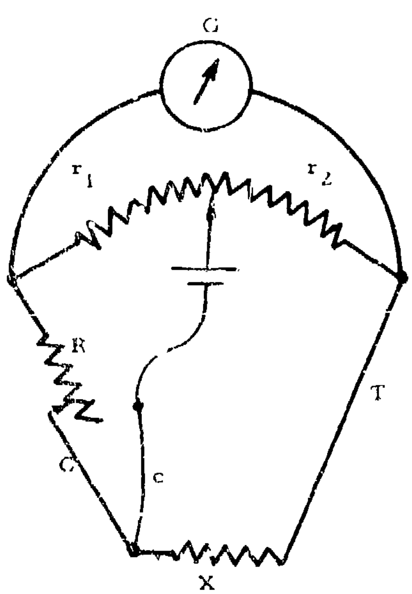

Fig. 2-109 Siemen's 3 Wire Lead Compensation Method with Wheatstone Bridge

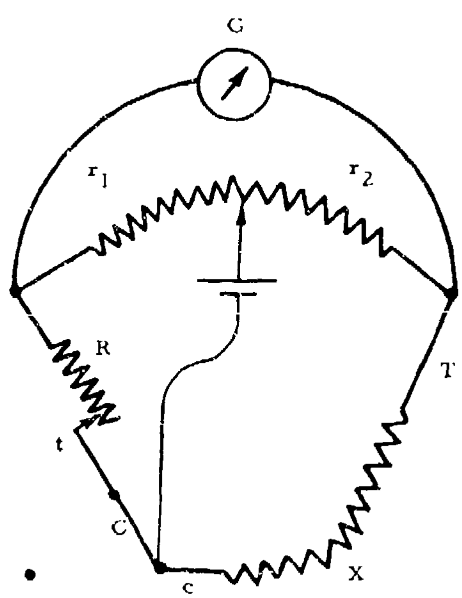

Fig. 2-110 Callendar's Lead Compensation Method with Wheatstone Bridge

The Callendar method, Fig. 2-110, makes use of a pair of dummy leads, Ct in Fig. 2-108b, that are connected in the measuring arm R of a Wheatstone bridge. The dummy leads Ct are made equal in resistance as the leads cT from the resistance element. The leads c and T and resistance element X are connected in the adjacent arm.

Then we have $$\frac{R + C + t}{r_1} = \frac{X + T + c}{r_2} . \qquad (2\text{-}60)$$

If r_1 is made equal to r_2, then R must equal X, thus eliminating the lead resistance from the measurement.

In the four wire method, Fig. 2-108c, two leads CT are current leads, and the other two leads ct are potential leads. These are connected to a Wheatstone bridge as shown in Fig. 2-111. The resistance R_a and R_b are adjusted to balance the bridge in Fig. 2-111a. and 2-111b. respectively. Then, the equation for Fig. 2-111a is,

$$\frac{R_a + C}{r_1} = \frac{X + T}{r_2} , \qquad (2\text{-}61)$$

and for Fig. 2-111b.

$$\frac{R_b + T}{r_1} = \frac{X + C}{r_2} . \qquad (2\text{-}62)$$

The ratio arms r_1 and r_2 are again made equal. Adding the above two equations we have

$$X = R_a + R_b/2 . \qquad (2\text{-}63)$$

The change in connections from 2-111a. to 2-111b. are made with a commutator.

In the potentiometer method, the resistance thermometer X, Fig. 2-112, is connected in series with a standard or known resistance R and a battery B. Precise measurements of the potential drops E_r and E_x across the two resistors R and X are made. Since the same current is maintained through two resistors, the unknown resistance can be easily determined by

$$X = E_x R/E_r . \qquad (2\text{-}64)$$

Further details on the use of bridge circuitry techniques in temperature measurements is presented in Appendix IV.

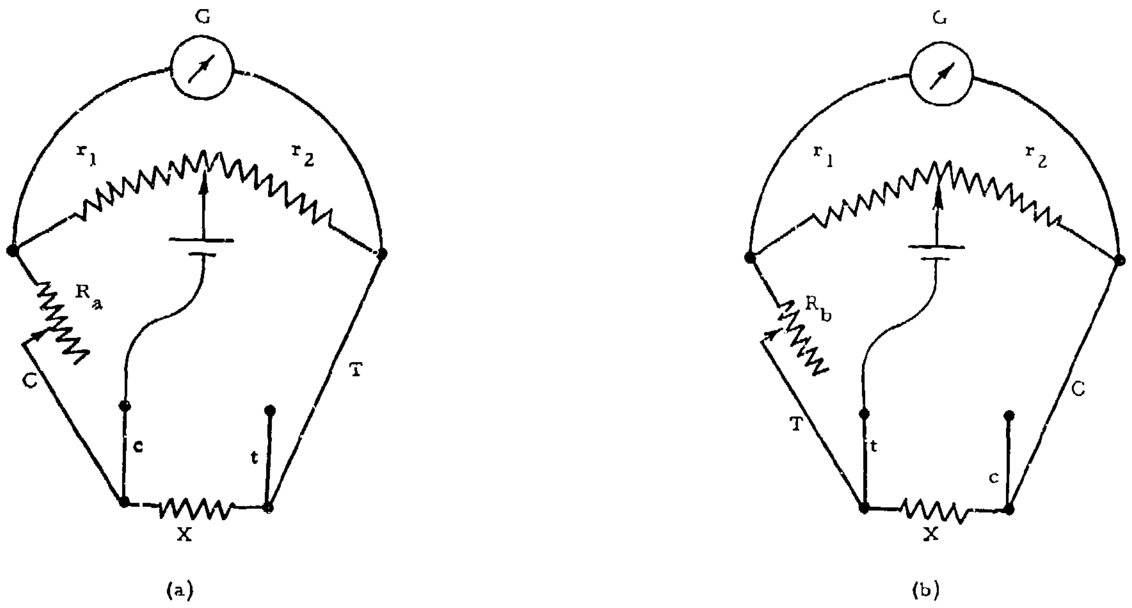

Fig. 2-111 Four Terminal Lead Compensation Method with Wheatstone Bridge

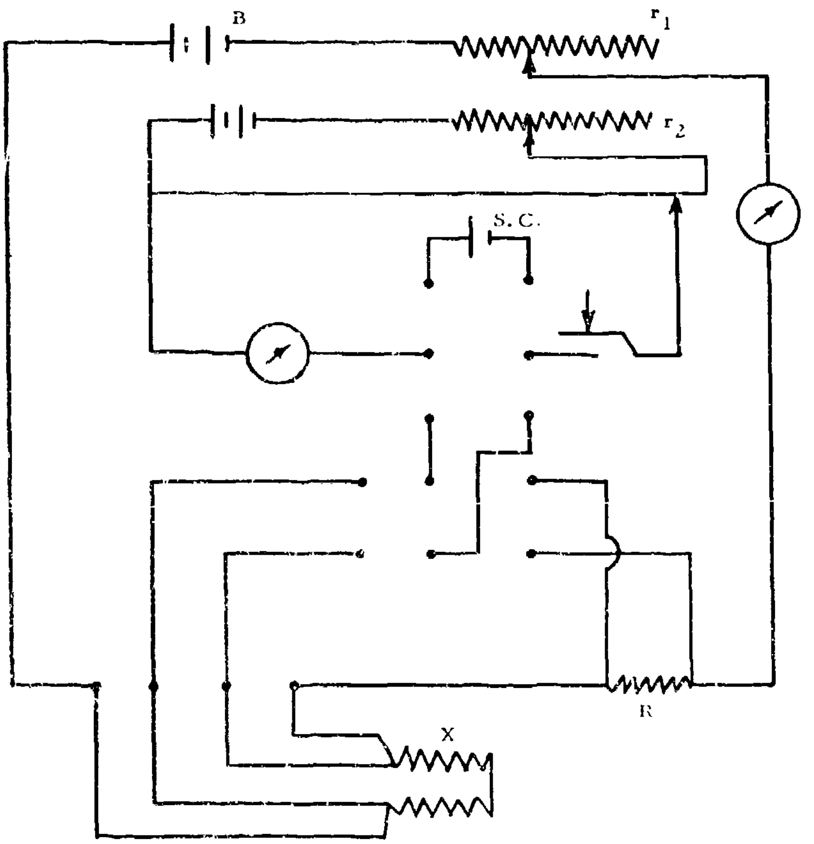

Fig. 2-112 Potentiometer Method of Measuring Resistance

The potentiometer method is very useful when the resistance varies over a wide temperature range. The precision of measurement is kept nearly constant over a wide temperature range. This method is capable of as high a sensitivity as the bridge methods; however, it is generally not as convenient to use. Another difficulty is the problem of eliminating stray emfs. which cause errors in measurement.

The resistance thermometer has several advantages over other types of temperature measuring devices. Its excellent accuracy makes it especially valuable in measuring small temperature differences although it is also suitable for measuring large temperature differences and high temperatures. Well-designed resistance thermometers have excellent stability. Unlike thermocouples, they do not need a reference junction. In general, this is usually the reason resistance thermometers are used instead of thermocouple in some industrial applications.

Disadvantages of resistance thermometers include relatively large volume compared to thermocouples which results in an average temperature over the length of the resistor rather than a point temperature, and the need for auxiliary apparatus and power supplies. The resistance element is usually considerably more expensive than a thermocouple. The electrical current through the resistor must be kept as small as possible in order to minimize error due to self-heating of the resistor. (A current of less than 10 ma is desirable to prevent sizable errors from self-heating). These errors may be considerable when the resistance thermometer is used to measure temperature in slow moving gas streams.

(7) Thermocouples

The principle operation of a thermocouple is based on the discovery by Thomas SeeBeck, in 1821, that an electric current flows in a closed circuit of two dissimilar metals when their junctions are at different are at different temperatures. Thus, by measuring the emf developed and knowing the variation of emf with temperature, a thermocouple may be used to measure temperature.

Three fundamental laws governing the operation of thermocouples have been formulated. These are:

(a.) The law of the homogeneous circuit.

An electric current cannot be sustained in a circuit of a single homogeneous metal however varying in section, by the application of heat alone.

(b.) The law of intermediate metals.

The algebraic sum of the thermoelectromotive forces in a circuit composed of any number of dissimilar metals is zero, if all of the circuit is at uniform temperature.

(c.) The law of successive or intermediate temperatures.

The thermal emf developed by any thermocouple of homogeneous metals with its junctions at any two temperatures T_1 and T_3 is the algebraic sum of the emf of the thermocouple with one junction at T_1 and the other at T_2 and the emf of the same thermocouple with its junctions at T_2 and T_3.

A simple thermocouple circuit is shown in Fig. 2-113. It consists of two dissimilar metals connected together at each end and an instrument for measuring the electromotive force (emf) developed when the junctions are maintained at different temperatures. If the instrument is kept at a uniform temperature, then all junctions in the instrument will be at the same temperature so that the emf developed will not be affected by the introduction of the instrument into the circuit. The reference junction of the thermocouple is usually maintained at a constant temperature, normally $0^{\circ}C$. The thermocouple is then calibrated to determine emf output as a function of temperature. Once this is known, then the device can be used to measure temperature.

Two methods of measurement of the emf generated by an thermocouple are direct and null methods. The direct method employs a high resistance meter to measure the emf and the null method depends on balancing one voltage against another in parallel with it. The direct method is inherently less accurate than the null method using the null method or potentiometric method. There is practically no current flow in thermocouple circuit when the potentiometer or is balanced. Therefore, variations in the thermocouple wire resistance are not as important. Also the galvanometer in the null method is used only to indicate zero current flow, while the meter in the direct method must accurately measure voltage and its accuracy depends on the inherent meter accuracy.

A special arrangement of thermocouples, called a thermopile, consists of two or more thermocouples in series. They are principally used to detect small amounts of radiant energy and are used as detectors in many radiation pyrometers. In this application a lens concentrates the radiant energy on the hot junctions through an aperature that shields the cold junction.

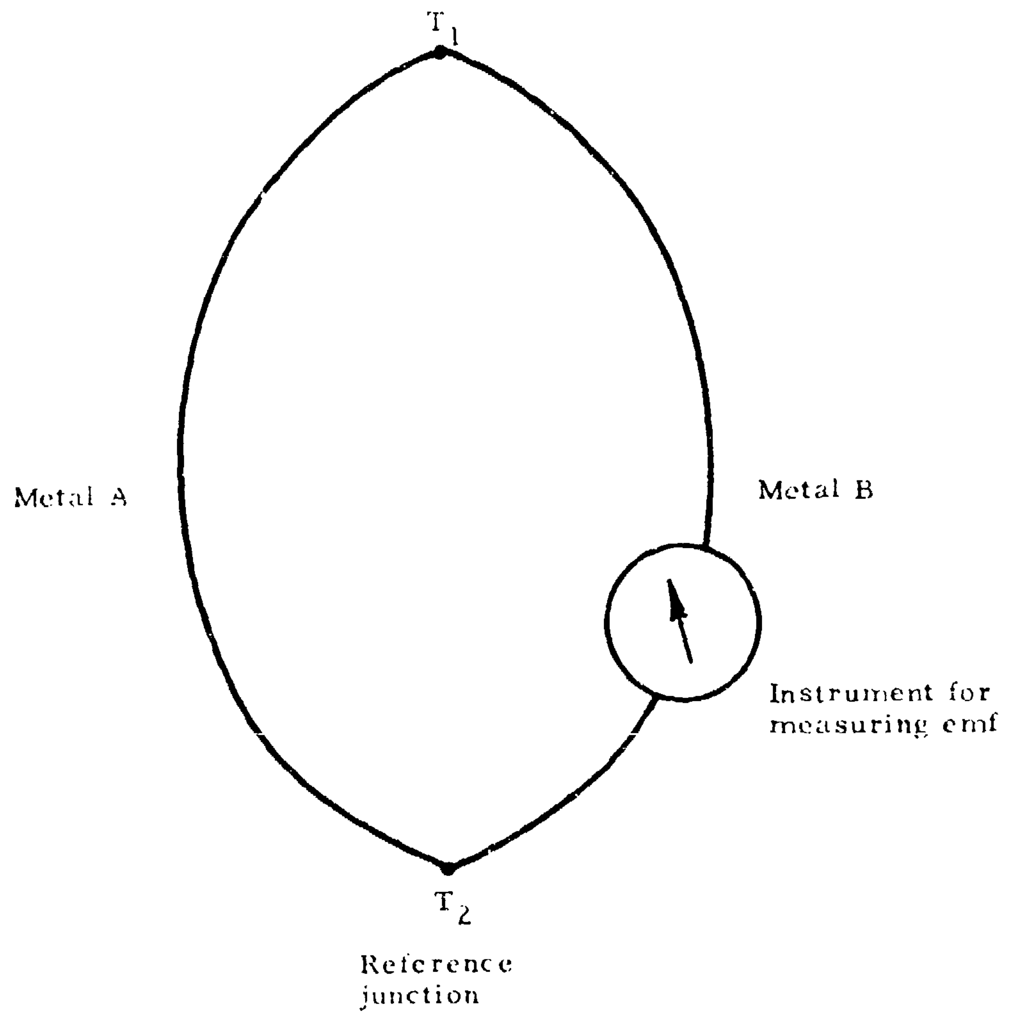

Fig. 2-113 Thermocouple Circuit

Thermocouples, in general, have advantages for use in temperature measurements such as: very stable, small size, an electric signal output, operation over a wide temperature range, flexibility as to mounting, ease of application, and low material cost. The principal disadvantages in the use of thermocouples are the need for cold junction compensation and the relatively small dc electrical output. Other disadvantages are the need for electrical measuring apparatus, calibration curves are based on empirical measurements although the curves are repeatable to tolerance accuracies, gradual change in readings due to alloys changing composition, and the need for potentiometer readings when good accuracy is required.

(8) Semiconductors

The theory of semiconductors rests upon the concept of energy bands in solid state materials. A brief discussion of the origin and significance of these energy bands are included in Appendix IV and further reference maybe found in the Handbook of Semiconductor Electronics, (Ref. 181).

An increase in temperature increases the conductivity of a semiconductor and vice versa. Semiconductors are therefore said to possess positive temperature coefficients of conductivity or conversely, negative temperature coefficient of resistivity.

Most semiconductor temperature measuring devices fall under the thermistor type and a discussion of these will follow shortly. However, a low temperature thermometer has been developed utilizing arsenic doped germanium, a material quite dissimilar to those used in ordinary thermistors. See reference 182 for a complete report and Section III of this handbook for application and description.

The semiconductor temperature measuring devices offer advantages of extremely small size and the relatively simple apparatus it requires for operation. The only significant dis[illegible]tage apparent at this time is that its response cannot be given by a simple equation, making calibration curves a necessity.

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181 L. P. Hunter, Handbook of Semiconductor Electronics, McGraw-Hill Book Company, Inc.

182 Kunzler, J. E., T. H. Geballe and G. W. Hull, "Germanium Resistance Thermometers Suitable For Low Temperature Calorimetry", Review of Scientific Insturments, Vol. 28 n 2, Feb. 1957.

Proposed work on this type thermometer includes a study of its stability upon cycling from room temperature to liquid helium temperature, a determination of its upper temperature limit, types with higher resistance ranges and a study of functional characteristics at lower temperature.

(9) Thermistors (Ref. 183 and 184)

Thermistor is a name given to thermally sensitive resistors made from sintered mixtures of metallic oxides such as TiO_2, MgO, NiO, Fe_3O_4, etc. The energy band theory used to describe the conduction mechanism in semiconductors does not apply to thermistor materials. Theory indicates that in their pure state they should be metallic conductors because of their unfilled valence band. Actually they have the properties of insulators.

In their mixture form, these elements have thermal properties similar to semiconductors since for limited ranges, their resistance is given by the following equation:

$$R = A\, e^{B/T} \qquad (2\text{-}65)$$

where

R = resistance
A = constant
B = nearly a constant for a given material
T = absolute temperature

Compare this to the semiconductor equation for resistivity:

$$e = A'\ e^{B'/T} \qquad (2\text{-}66)$$

where

e = resistivity
A' = constant
B' = E/2k

Figure 2-114 shows a typical thermistor specific resistance variation with temperature.

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183 Same as Reference 180

184 Sapoff, Meyer, "The Thermistor--A Specialized Semiconductor Sensor", Military Systems Design, July/August 1961

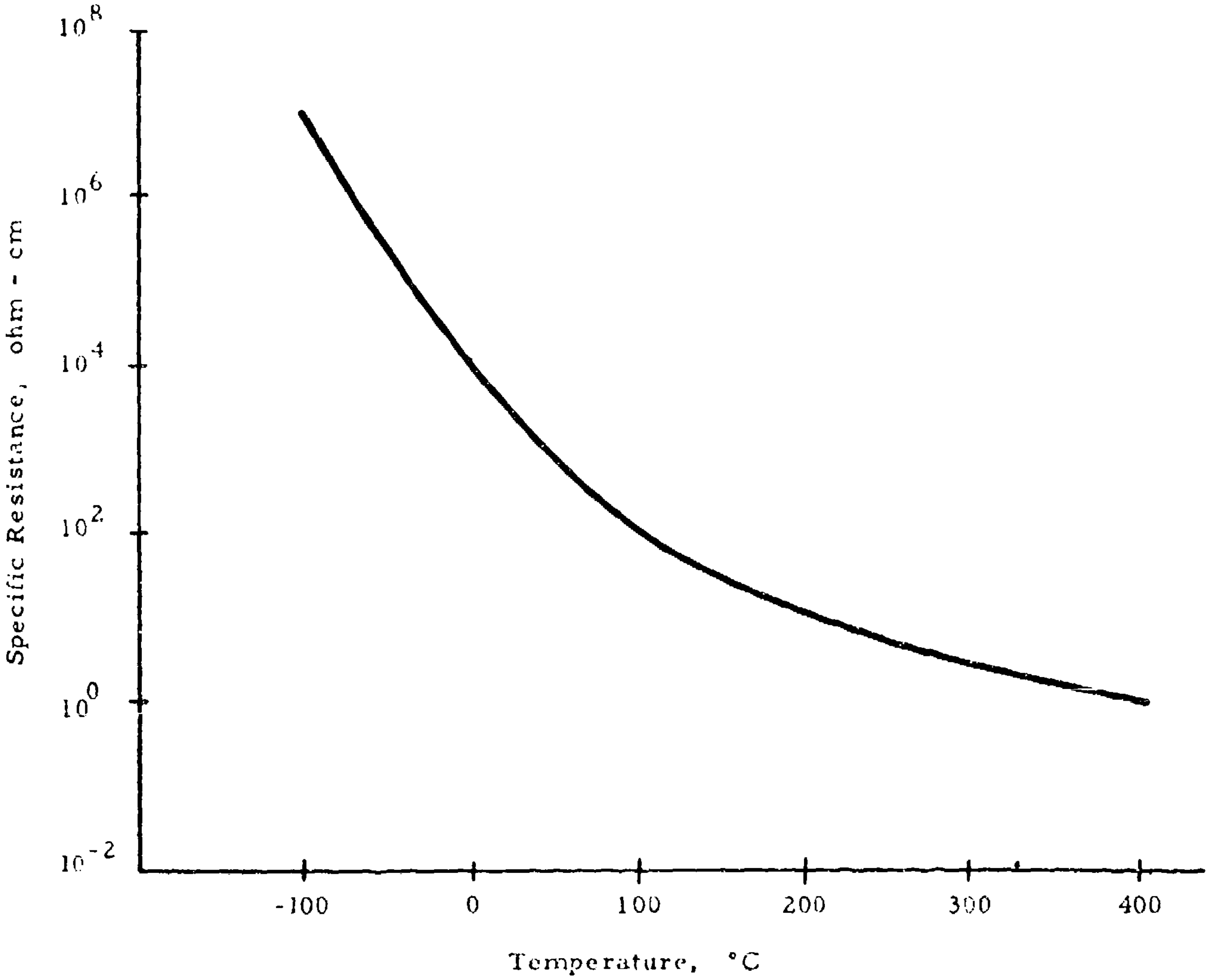

Fig. 2-114 Typical Thermistor Characteristic Curve (Fenwal Electronics)

There are many ways in which thermistors are used to measure temperature. All systems, of course, utilize the thermistor's property of varying resistance with temperature. One straightforward and very sensitive method employs a thermistor in a simple Wheatstone bridge. The resistance measurements are correlated to temperature by means of calibration curves which, because of a thermistor's non-linearity, should be made for each thermometer. This method is quite accurate (0.001°C), but because of its need for a calibration curve, it maybe less convenient than other methods. Using suitable shunting resistors, to compensate for differences in thermistors resistance-temperature characteristics, one may construct a bridge circuit temperature measuring device corresponding to a single calibration curve. See Section III on Applications for detailed discussion of thermistor compensation to arrive at desired resistance verses temperature characteristics.

Still another method eliminates the need for separate calibration curves. Connecting a thermistor in series with a fixed resistor results in an inflexion point in the curve relating current temperature. If a Wheatstone bridge with an arm consisting of an arm and a series resistor is balanced at this point of inflexion, bridge output will be linear with respect to slight variation in temperature. The accuracy of this method is somewhat better than the previous one (0.04°C); however, the temperature range is substantially reduced.

Thermistors possess many advantages over other temperature measuring devices, the foremost being their extremely high temperature sensitivity. It is about ten times higher than metallic resistance thermometers, and it enables thermistors to be used in comparatively simple measuring circuits. Another advantage that thermistors offer is that they can be manufactured in any size and shape. The three most common shapes are rods, discs, and beads. The bead shape has been made in sizes as small as 0.010 cm in diameter. If fast response times are desired, flake thermistors can be made with thermal relaxation times in the order of a few milliseconds.

Thermistors can also be used for remote indication, since their resistances at normal operating temperatures are high enough to make lead resistances appear negligible. Their stability at normal temperatures is also good for they hold their original calibration for long periods of time.

The chief disadvantage appears to be their non-linearity, but many systems have been devised to compensate for this. The low temperature limit of the thermistor comes about by the insensitivity that occurs in the measuring system when the thermistor's resistance becomes too large. The upper temperature limit is set by an instability that results when thermistors are subjected to sufficiently high temperatures.

Materials of ceramic composition belonging to the alkali-aluminum-silicate family, exhibit resistivity characteristics similar to those of thermistors, even to the similarity in equations, but their most valuable feature is that they can be used at temperatures as high as 1500°C and possibly higher. Further study and development of these materials is needed to control in their manufacture, the many sensitive variables such as composition, impurity concentration, time of firing, and temperature of firing of the ceramic.

(10) Sensitors

Sensitor is the trade name given by Texas Instrument Inc. to a semiconductor product which exhibits a positive temperature coefficient of resistance. They achieve this by introducing carefully controlled amounts of Boron impurities into Silicon semiconductors. At temperatures below -150°C, the Sensitor has a negative temperature coefficient much the same as other positive and the element acts as a highly sensitive metallic resistance thermometer.

Sensitors are used in almost exactly the same circuits and applications as thermistors. The advantage of Sensitors over thermistors is that they can be easily manufactured to close tolerances. Further comparisons between Sensitors and thermistors indicate a slightly better linearity in the former, but a slightly higher sensitivity in the latter. The lower temperature limit is -150°C due to the temperature coefficient changing from positive to negative at this point. Instability determines the upper limit at 200°C.

(11) Therminonic Emission

Electrons in the valence band are free to travel throughout a material, but at the boundaries of the conductor, the potential energy barrier rises to a value large enough to prevent electron emission from its surface. By heating, however, it is possible to raise the energy of an electron to a value sufficient ot overcome the barrier. The difference between the energy required to overcome the barrier and the Fermi energy level is called the work function of the metal. It is possible to develop expressions for the number of electrons that arrive per unit time at a unit surface. See Appendix of this report for a detailed discussion of these expressions and relations. With further derivation one may arrive at an equation relating the emission current density with temperature.

A fundamental circuit of a vacuum diode is shown in Fig. 2-115. No heater is shown since all the heat is supplied by the object whose temperature is being measured. The voltage supply is necessary to direct the electron flow from the cathode to the anode, and the current reading on the ammeter is a measure of the cathode temperature.

The advantages to be found in thermionic emission thermometry include high temperature measuring capabilities, linear operation, and simple operational circuitry. A major disadvantage is the fact that the characteristics of a diode change after it is used for a sufficiently long time. This would tend to affect the accuracy of the device. Also affecting the accuracy would be the photo-emission and field emission effects of a low work function cathode.

The area of thermionic emission thermometers have many problems that must be solved before they can be considered practical. One of these problems is the development of cathode materials that are suitable for various temperature ranges. Along with this, the materials must have extremely long life expectancies to prevent the inaccuracies that result from cathode evaporation. Another problem is the development of convenient and compact enclosures which allow for anode cooling.

(12) Magnetic Techniques

There are three distinct forms of magnetism: ferromagnetism, paramagnetism, and diamagnetism. Externally they can be distinguished by the value of magnetic susceptibility in a material. A ferromagnetic substance has a susceptibility that is not constant but is often very large. This differs from a paramagnetic material which has a very small, positive susceptibility, and a diamagnetic material which has a very small negative susceptibility. The susceptibility of diamagnetic materials has been found to be almost independent and will not be discussed in connection with temperature sensing. A representative paramagnetic temperature measuring system may consist of a one-inch sphere of paramagnetic salt, chromic methylammonium alum; a mutual inductance bridge; a low frequency signal generator; a galvanometer; and an amplifier. The schematic diagram is pictured in Fig. 2-116. The salt, represented in the figure by S, is used as the core of a mutual inductance M_1 , which is put in parallel with a variable mutual inductance M_2. They are both fed by a low frequency (200 cps) signal generator. If the mutual impedance of M_2 do not equal of M_1 , a signal will appear across the amplifier where it will be amplified and sent to a vibration galvanometer to indicate a deflection. Variations in temperature will vary the mutual inductance M_1 because of the variation in magnetic susceptibility

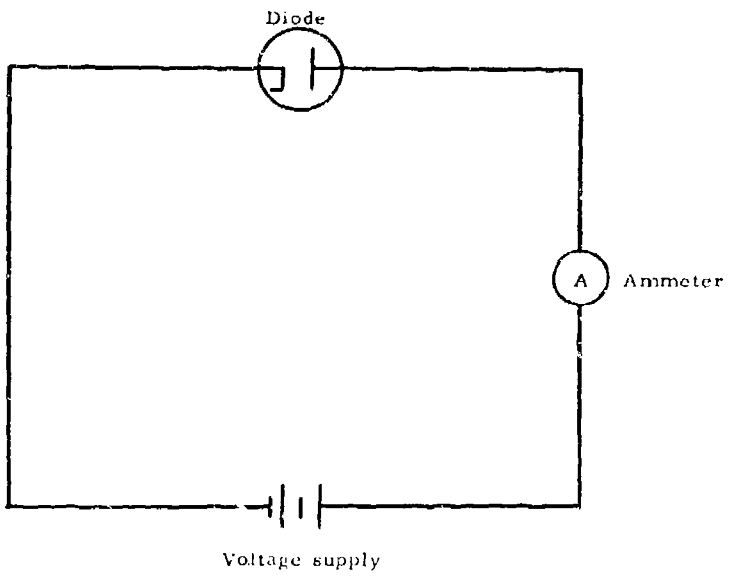

Fig. 2-115 Simple Diode Temperature Measuring Circuit

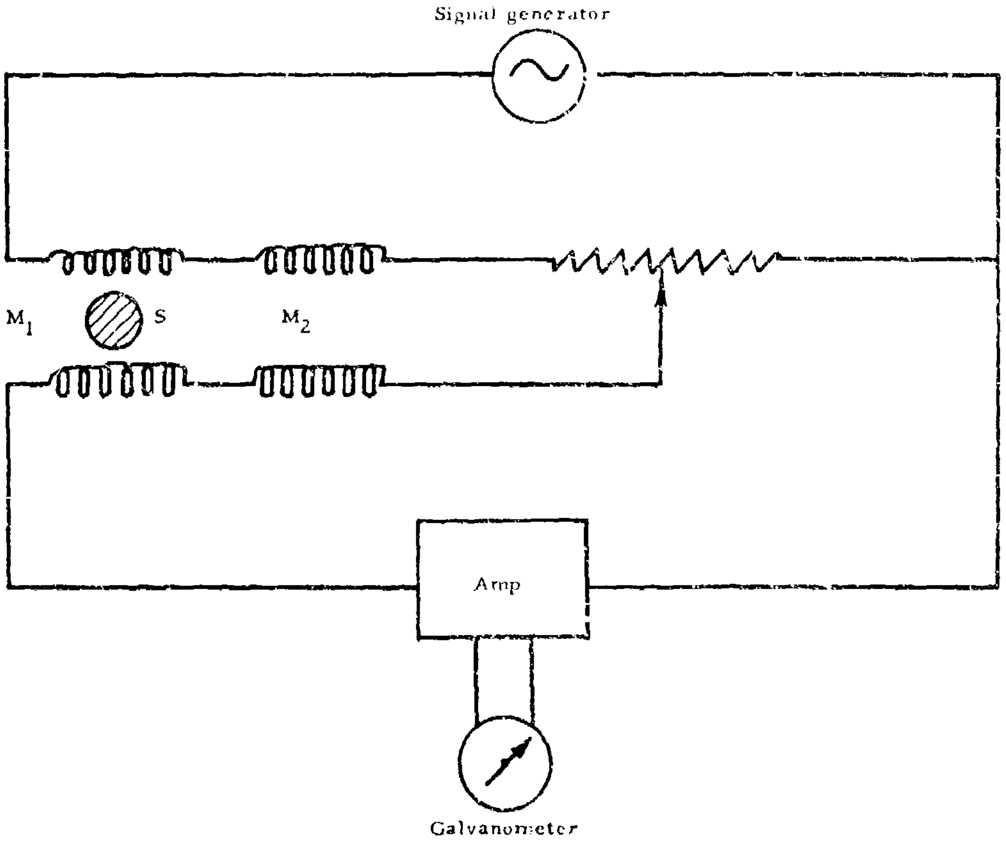

Fig. 2-116 Mutual Inductance Bridge

of the paramagnetic core. After adjusting the variable mutual inductance M_2 and the variable resistor R (to account for phase shift in M_1) until the galvanometer nulls, a reading can be taken of M_2 and interpreted in terms of temperature by means of calibration curves.

The principal advantage of this system is its extreme accuracy and sensitivity at very low temperatures. While it is true that resistance thermometers can be used at equivalent temperatures, they do not posses the linearity of the paramagnetic salt.

The very narrow temperature range may be the most important disadvantage of this system and it is a minor one. The upper limit of the temperature range would have to be set by the loss of magnetism and its consequent adverse effect upon the sensitivity of the system. The lower temperature will theoretically be set by the Curie Point, although physicists (Ref. 185) believe that it will probably be determined by the crystalline field splitting of the ground state spin quadruplet.

Ferromagnetic techniques concern the use of ferromagnetic substances such as iron, cobalt, and nickel. The graph in Figure 2-117 shows that the relative magnetization of a ferromagnetic material decreases as the temperature is increased, and eventually approaches zero at the Curie temperature. This agrees very well with experimental evidence, although it has been found that a ferromagnetic material does not lose all its magnetism but becomes paramagnetic at, and above the Curie Temperature. The inverse relationship of magnetization to temperature is an indication that thermal vibration of the molecules oppose their alignment of their magnetic moment. A simple temperature measuring system, Fig. 2-118, employing ferromagnetic techniques consists of two coils wound on a ferromagnetic core. A low frequency signal is supplied to one of the coils which in turn induces a voltage across the other. The induced voltage is directly related to the magnetic susceptibility of the ferromagnetic core, which is inversely proportional to the temperature of the core. Here there is an inverse relationship between the induced voltage and the temperature. The voltage is taken off the second coil by a voltmeter and is translated to temperature by a calibration curve.

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185 Davis, T. P., "The Carbon Arc Image Furnace", Proceedings of Symposium on High Temperature, A Tool For The Future, 1956, Berkeley, Calif.

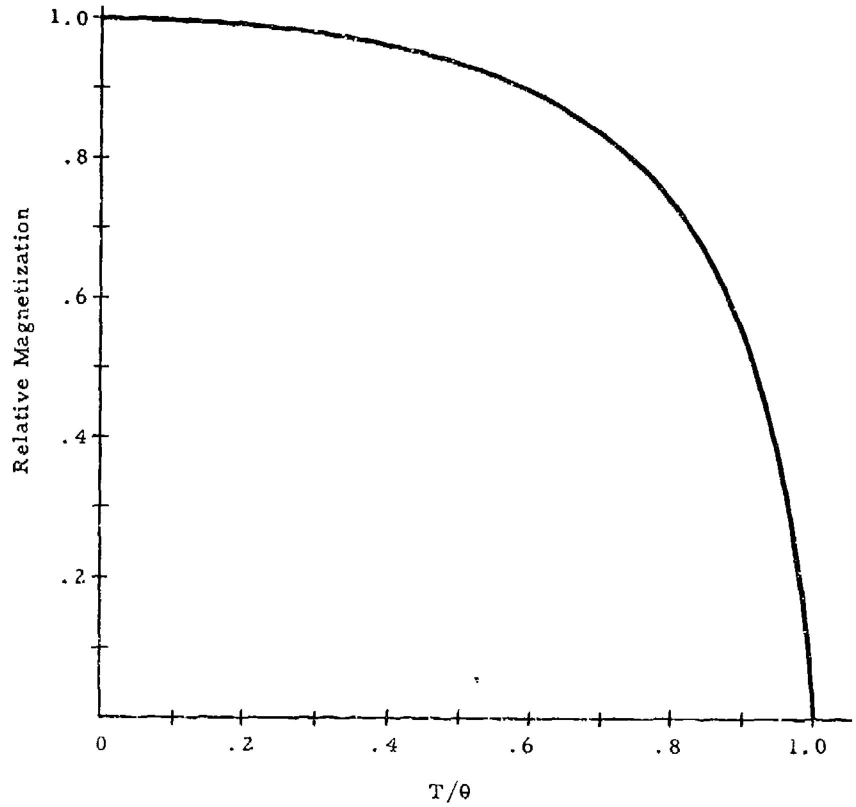

Fig. 2-117 Temperature Variation of Ferromagnetism

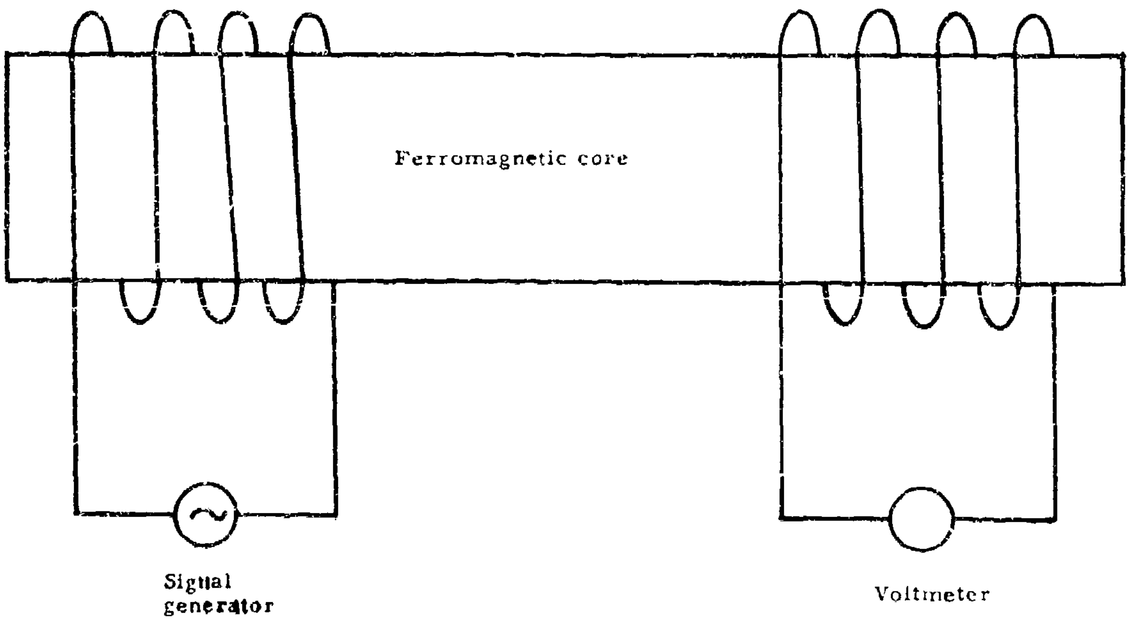

Fig. 2-118 Ferromagnetic Thermometer

The primary advantages of this technique are its usefulness at moderately high temperatures and its simplicity of construction. From the relative magnetization versus temperature curve it can be seen that a ferromagnetic material has a very large temperature sensitivity near the Curie point, but the sensitivity decreases rapidly as the temperature is lowered. It has been estimated (Ref. 186) that the useful temperature range is limited at the lower end by temperature of approximately 50°C below the Curie point. This lower limit is set by sensivitity considerations and the upper limit is of course set by the Curie point. The Curie temperatures of iron, nickel, and cobalt are 770°C, 350°C, and 1120°C respectively. To adjust the Curie points and hence the useful temperature range of these materials, various alloys are used. With such alloys, Curie points as low as 60°C are common. The low temperature usefulness of ferromagnetic materials and alloys is curtailed at temperatures lower than -75°C because of their irreversibility.

(13) Thermal Noise Thermometer

Thermal noise is a fluctuating voltage or current of random amplitude and phase. Such fluctuations are associated with any resistive element which is at an absolute temperature T. The thermal noise in resistors is generated by the random motion of conduction electrons which result from their collisions with the crystal lattice. The random motion of the electrons corresponds to random electrical current or voltage and hence to a noise source. The mean square value of thermal noise current, or voltage output from a resistor in thermal equilibrium at a temperature T, has been derived by Nyquist (Ref. 187). The mean square noise voltage is proportional to the absolute temperature and this noise voltage can be measured very accurately. Experimental measurements of noise output from resistors have been performed by J. B. Johnson (Ref. 188) in the temperature range from -180°C to 100°C.

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186 Jackson, L. R. and H. W. Russel, "Temperature Sensitive Magnetic Alloys and Their Uses", Instruments, Vol. 11 n 11, November 1938

187 Nyquist, H., "Thermal Agitation of Electric Charge In Conductors", Physical Review, Vol. 32, July 1928

188 Johnson, J. B., "Thermal Agitation of Electricity In Conductors", Physical Review, Vol. 32, July 1928

Recently at Armour Research Foundation the linearity of the noise output of a resistor as a function of temperature was measured up to 1300°C (Ref. 189). All the experimental measurements confirmed Nyquist's relation within the experimental error. A noise thermometer for high temperature and high pressure have been designed by Garrison and Lawson (Ref. 190). The accuracy of the noise thermometer has been reported as 0.1 percent up to 1000°C. A similar noise thermometer (Ref. 191) has been investigated by the National Bureau of Standards to determine its applicability for measurements in the 700°C to 1200°C temperature range with three place accuracy. Recently a low temperature noise thermometer (Ref. 192) has been designed to measure temperatures as low as the boiling point of liquid helium. At that point a deviation on only 8 percent from the accepted value has been reported.

The noise thermometer has possibilities as an absolute (requiring no calibration) temperature measuring device. Very high accuracies have been obtained. Limitations of the accuracy and hence the usefulness as an absolute temperature standard is primarily dependent on the accuracy of the noise thermometer is determined by the temperature stability of currently resistive materials.

c. Thermal Radiation Method

(1) Radiation Detectors

Electrons can be excited to higher energy levels by light as well as heat. For photoemission to occur, the photons falling on a conductor must impart to the free electrons of that material enough energy to overcome the potential barrier at its surface. The minimum energy of the photon must therefore be the work function of the material. By lowering the work function, the frequency needed for photoemission is also lowered, and if the work function is lowered sufficiently, a electron emission will take place for frequencies in

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189 Zucker, H., et al., Design and Development of a Standard White Noise Generator and Noise Indicating Instrument", IRE Trans. On Instrumentation, Vol. 1-7, Dec., 1958

190 Garrison, J. B. and A. W. Lawson, "An Absolute Noise Thermometer For High Temperatures", Review of Scientific Instruments, Vol. 20, 1949

191 "High Temperature Thermodynamics Technical Report II" NBS Report 3431, NBS Project 0301-20-2674, July 1954

192 Patronc's, E. T., et al., "Low Temperature Thermal Noise Thermometer" Review of Scientific Instruments, Vol. 30, July 1959

the infrared region, thereby enabling the device to be used as a radiation detector. The only difference between photoemissive cathode does not have to be brought to the temperature of the test object. A photo tube circuit is very similar to that of a thermonic diode circuit. Because of the extremely low currents (micro amps) that result in photoemission, it is easier to measure the voltage drop across a large resistor than to try to measure the current. Large currents can be obtained by the use of photomultiplier tubes, which are simply carefully designed phototubes employing the principle of secondary emission.

The fact that phototubes do not have to be in thermal equilibrium with the test object makes them ideal for the measurement of high temperatures. They are used in optical pyrometers and in radiation pyrometers. However, somewhat limited by the fact that their spectral response does not extend very far into the infrared region. Their fast response time also increases their usefulness in temperature measurement. Disadvantages of optical pyrometers include the precautions that must be taken in clearing obstructions such as smoke, fumes, etc. from the radiation path, keeping lens free from dirt and grease, and the relatively high cost of the optical systems. The lower temperature limit of visible light (about 760°C) sets the lower limit upon optical pyrometer systems using phototubes. Their highest temperature is limited by the emission saturation of the tube. The temperature extremes of a phototube radiation pyrometer would have to be set by the spectral response of the tube.

Light photons of sufficient energy, upon striking a semi-conducting material, are able to excite electrons across the forbidden energy gap, therby increasing the conductivity of the material. Semiconductors with small gaps can be used for frequencies in the infrared region and are therefore useful in radiation pyrometers. A photoconductive cell acts somewhat as a remote action thermistor, and seemingly can be used in the same types of circuits as thermistors (bridge circuits, series circuits, etc.). Lead sulfide is a material which exhibits photoconductive properties at radiation frequencies as low as 500 cycles per second. The advantages of a lead sulfide photocell are its extremely small size, ruggedness, and infrared sensitivity. Temperature limitations upon a photoconductive cell are dependent upon its spectral response. A third type radiation detector is the photovoltaic cell. It operates on a principle similar to that of contact potential in metals. A N-type semiconductor with a Fermi Level somewhat higher than that of a metallic conductor is placed in contact with the metallic conductor. Electrons flow from the semiconductor to the metal until the two Fermi Levels are equal, making the semiconductor and metal a single thermodynamic system. In doing so, a potential barrier is formed at the junction of the metal and the semiconductor, which halts further flow of electrons between the two. Upon illumination, the light photons excite electrons

across the energy gap, thereby greatly increasing the electron and hole concentration in the semiconductor, and also upsetting the thermodynamic equilibrium of the system. Since these excited electrons are unable to flow across the junction barrier and neutralize the effect of the illumination, thermodynamic equilibrium is again achieved by a rise occuring in the semiconductor's energy levels. The rise continues until the free electron and hole concentrations in the semiconductor equal those at the same energy levels in the metal. A voltmeter across the metal and the semiconductor will indicate a voltage drop equivalent to the difference in Fermi Levels of the two. The maximum voltage drop is practically realized to be the voltage equivalent of one half the forbidden energy gap in the semiconductor. As was the case in the other photoelectric devices, photovoltaic cells have a radiation frequency dependence.

(2) Line Reversal Pyrometer

The line reversal pyrometer is a device for the measurement of gas temperatures above 1000°K. In principle it is somewhat similar to the optical pyrometer in that it compares the radiation from a gas with that from a calibrated reference source. Unlike a solid, a gas emits or absorbs radiant energy at only certain descrete wavelengths. When a black body is viewed through a gas and the gas is at a higher temperature than the black body, the gas will appear bright against the background of the black body at the wavelengths that the gas emits energy. If the gas is at a lower temperature than the black body, the gas will appear dark against the background of the black body at the wavelengths the gas absorbs. By adjusting the temperature of the black body until no difference in brightness exists between the gas and the black body, the gas temperature is equal to that of the black body, and the gas temperature may then be determined by measuring the black body temperature. The determination of the point of equal brightness is most conveniently made by using a spectroscope. Radiation from a black body appears as a continuous spectrum and the radiation emitted or absorbed by the gas apprears as bright or dark lines. At the points of equal brightness, the lines disappear against the background of the continuous radiation.

The upper temperature which may be measured by the line-reversal method is limited by the calibration radiator. Tungsten ribbon lamps cannot be used beyond 3000°K. Improvement in this respect depends on the development of radiator sources to work at higher temperatures. Another improvement would be to eliminate the need for manual adjustment required for matching the gas and lamp brightnesses. (Ref. 193)

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193 Buchele, D., A Self-Balancing Line-Reversal Pyrometer, NACA TN 3656, August 1956

(3) Optical Pyrometers

An optical pyrometer is a device in which the temperature of an object is determined by comparing the visible radiation from the object with that from a calibrated reference source. The commonly used optical pyrometers consist of an optical system which forms an image of the object viewed in the instrument. A lamp is used as a reference source and is positional so that the lamp filament is in the focal plane of the image. The lamp filament and the object whose temperature is to be measured can be seen simultaneously through the eyepiece of the optical pyrometer. The temperature of the object is measured by adjusting either the brightness of the lamp filament or the image of the object viewed until they coincide. At the point of equal brightness the lamp filament disappears against the background of the object viewed.

Two types of disappearing filament pyrometers are marketed. In the type made by the Leeds and Northrup Company, a slide wire resistor is used to adjust the filament current in the lamp to make the brightness match. A potentiometer in the instrument is calibrated to give the temperature of the object when the potentiometer is balanced against the slide wire resistor. In the optical pyrometer made by the Pyrometer Instrument Company, the brightness of the image of the object whose temperature is being measured is adjusted by rotating a wedge shaped absorbing screen placed between the lamp filament and the object. The absorbing screen is calibrated to give the temperature of the object when the brightness match is made.

With either optical pyrometer, at the point of equal brightness, the color of the filament is not necessarily the same as that of the object viewed. Since this would make precise matching of the reference source and object brightness difficult, most of the better instruments include a monochromatic filter. With this arrangement the brightness match is made in a narrow bank of wavelengths which is usually located in the red end of the visible spectrum.

The most important advantage of the optical pyrometer is that it can be used to measure the temperature of a material without being in contact with it. The disadvantage of the optical pyrometer is that the emissivity of the object can be obtained, and that the instrument does not measure temperature automatically, but requires a manual adjustment. Use of photo tubes for automatic balancing are under development. (Ref. 194)

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194 Blum, N. A., "Recording Optical Pyrometer", Review of Scientific Instruments, Vol. 30 n 4, April 1959

(4) Total Radiation Pyrometers

A total radiation pyrometer consists essentially of a sensing element for detecting total radiation energy and usually a mirror or lens for focusing the radiation on the sensing element. The sensing element can be anything that gives a consistent signal from the radiation received. Thermocouples and thermopiles are most often employed, but in some cases thermistors, bolometers, and spiral wound bimetallic strips have been used. These sensing elements produce a signal by undergoing a temperature change from the radiant energy received. Since some time lapse is required for the temperature change to occur, the signal from these devices lags behind the radiation received. By making the mass of the sensing element as small as possible with respect to the surface area of the element, the response time has been made as small as possible with respect to the surface area of the element, the response time has been made as small as 0.4 seconds.

The temperature range over which the pyrometer can be used does not seem to have any theoretically limit. Commercial instruments are available which taken together, can be used from ambient to 4100°K. They indicate temperature remotely and therefore do not require physical contact with the material whose temperature is being measured. Another advantage is that they do not require manual adjustments, as optical pyrometers do, but give temperature readings directly. A disadvantage of a radiation pyrometer is that the emissivity of the object whose temperature is being measured must be known if the object is not a black body.

(5) Two-Color Pyrometer

The two-color pyrometer does not respond to the intensity of radiation received by the instrument, but instead is calibrated to indicate a temperature in terms of the ratio of radiant intensity at two different wavelength bands. As a result this instrument has a smaller dependence on emissivity than the optical pyrometer. The two-color pyrometer is also suitable for automatic process control because it does not require manual adjustment.

A two-color pyrometer usually consists of two filters which transmit in the red and blue portions of the visible spectrum. In the pyrometer made by the Shaw Instrument Company, the filters are mounted on a rotating disk. A photocell placed behind the disk delivers a fluctuating output due to the difference in radiant intensity transmitted by the two filters. Feed back in the electrical circuitry causes the average amplitude of the amplified signal to be constant. The fluctuation of the amplitude is then a function of only the ratio of the radiation received at the two wavelengths. The amplified fluctuation of the

signal is then fed to a meter which is calibrated to give the temperature of the object. The Shaw Instrument can be used to measure temperatures in the range from 760° to 3600°C.

(6) Microwave Radiometer

The microwave radiometer is based on an extension of Nyquist's theorem of thermal noise in resistors which also include the resistance of an antenna. The radiation impedance of an antenna is a function of its surroundings. For instance, if an antenna is surrounded by a perfect conductor, its impedance is zero since no power can be transmitted. If an antenna is surrounded by a perfect absorber its radiation impedance is equal to that which can be calculated for the case of the antenna in free space. If the surrounding of the antenna is at a nonuniform temperature, the radiometer will measure an effective temperature which will also be function of the antenna gain. The effective temperature is obtained from the power delivered by the antenna when connected to a matched load.

A block diagram of a microwave radiometer is shown in Fig. 2-119. The device is known as Dick's Radiometer (Ref. 195). The radiometer is a comparison instrument which compares the noise received by the antenna with the noise produced by the rotating absorbing wheel which acts as a resistive termination for the waveguide. The absorbing wheel is driven by a motor at a 30 cps rate, and is so shaped that it produces a signal with nearly square wave modulation. The square wave is symmetrical such that the waveguide is terminated half of the time by the resistance of the absorbing wheel kept at room temperature, and half of the time by the antenna resistance. If the noise received by the antenna is of the same magnitude as the noise of the absorbing wheel, no 30 cps noise modulated signal is fed into the receiver. The advantage of the method is that it is possible to discriminate between the noise generated by the receiver which is not modulated. With a 13 db noise figure of the receiver and a time constant at the output of the second mixer of 215 seconds, the accuracy of the temperature measurements has been with 0.4°K. Greater accuracies have been obtained with a radiometer at 8000 mc using traveling wave tube amplifiers (Ref. 196). The applications of radiometer have been primarily in radio astronomy to determine the temperature of various planets. A microwave radiometer could, in principle, be used to measure temperature of small objects which are in thermal equilibrium. The advantage of the radiometer would be that it does not require direct contact with the object, and therefore could measure very high temperatures. However, the beam width of the antenna would have to be very small and hence would require very short microwave wavelength and complex instrumentation.

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195 Dicke, R. H., "The Measurements of Thermal Radiation at Microwave Frequencies", Review of Scientific Instruments, Vol. 17, July 1946.

196 Drake, F. D. and H. I. Even, "A Broad-Band Microwave Source Comparison Radiometer For Advanced Research in Radio Astronomy", Proc. of IRE, Vol. 46, January 1958.

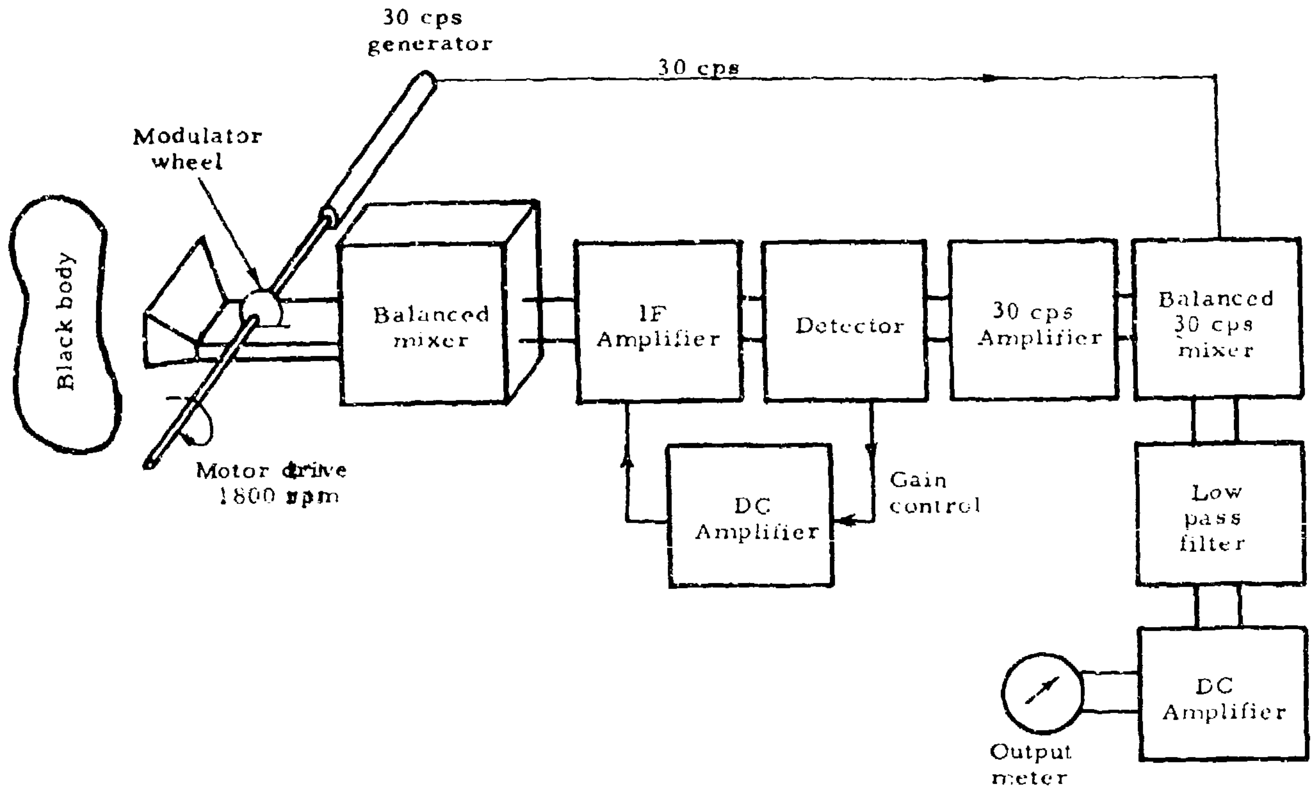

Fig. 2-119 Schematic Diagram of Dicke's Radiometer

(d) Miscellaneous Methods

In this section a few miscellaneous methods for temperature measurements will be discussed.

Cooled probes are devices for measuring the temperature of gases. The purpose of cooling the probe is to overcome the temperature limits of uncooled probes such as thermocouples and resistance thermometers. The maximum temperature that can be measured by an uncooled probe is determined by the material of which the probe is made. Cooled probes, however, do not come to the temperature of the gas, and can therefore be immersed in a gas at a temperature that would destroy an uncooled probe. Two types of cooled probes are the cooled gas and pneumatic pyrometers. A cooled gas pyrometer is describes in Ref. 197 and a sketch shown in Fig. 2-120. This device consists of a water cooled tube through which the gas whose temperature is being measured is aspirated. A thermocouple is placed near the outlet end of the tube where the gas has been cooled well below its inlet temperature. The temperature of the entering gas is calculated from the temperature of the gas at the thermocouple. A knowledge of the variation with temperature of the thermal properties of the gas (thermal conductivity, specific heat and density) is required up to the temperature to be measured. A cooled gas pyrometer cannot be used in gases where a chemical reaction is in progress. If combustion has taken place it must be complete where the probe is inserted or the combustion may continue in the probe and, by the heat released, cause the indicated temperature to be in error. The measurement of gas temperatures in excess of 2200°C may be possible if the thermal properties of the gas are known up to the temperature of the gas. Above 3000°C, however, the gas may begin to dissociate. A dissociated gas would start to recombine in the cooled tube and release heat. This would cause the indicated temperature to be in error.

Pneumatic probes are used to measure gas temperatures. They consist of two flow constrictions connected in series and separated by some device for reducing the temperature of the gas before reaching the second constriction. The flow constrictions are either nozzles or orifices, and the gas is drawn through them by a vacuum pump. Subsonic flow of a gas through any constriction is determined by the total temperature, total pressure, and static pressure of the gas at the constriction. After the gas passes through the first constriction, it is cooled from its inlet temperature down to a value at which it can be measured by a thermocouple at the second flow constriction. By measuring the total temperature, static and total pressures at the second constriction, the mass flow

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197 Krause, L. N., R. C. Johnson and G. E. Glawe, A Cooled Gas Pyrometer For Use In High Temperature Gas Streams, NACA TN 4383

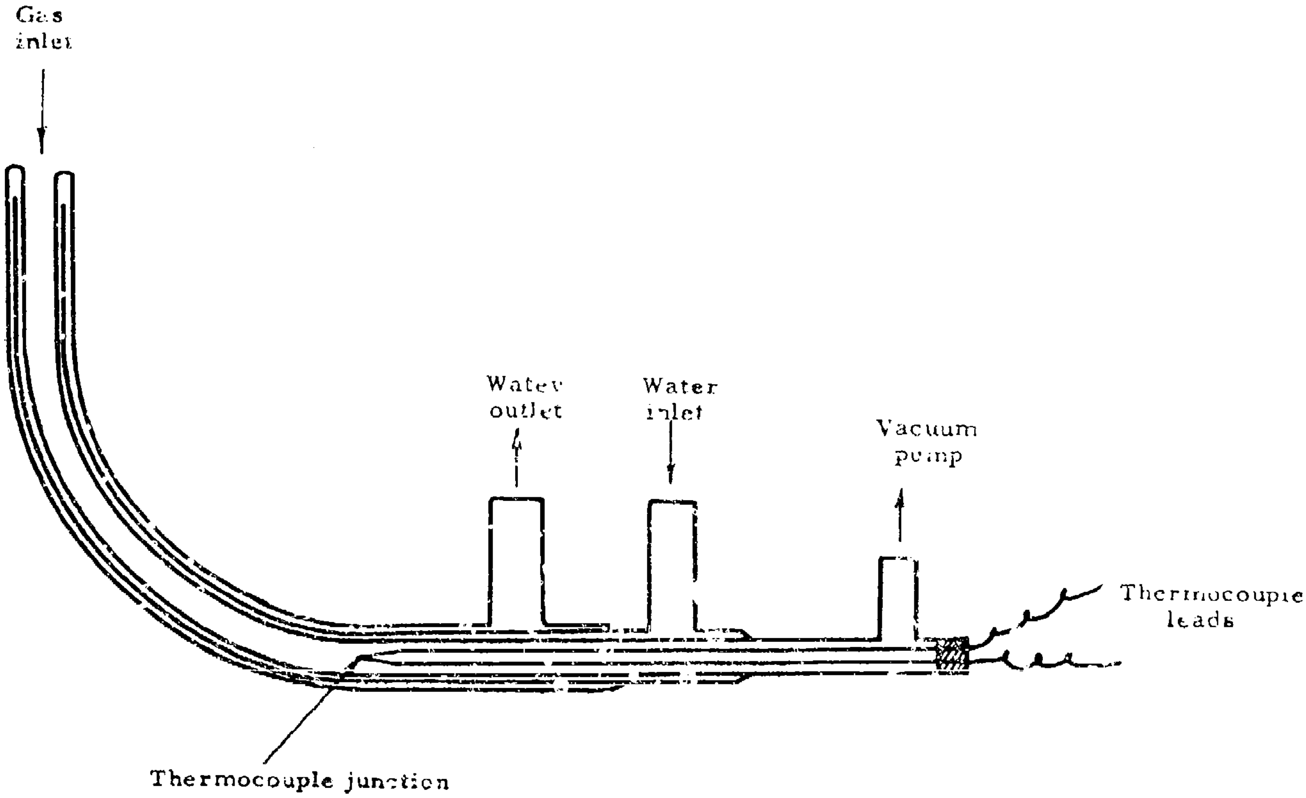

Fig. 2-120 Sketch of Cooled Gas Pyrometer

of the gas can be determined. The principle involved in the operation of pneumatic and sonic flow probes is that since the flow constrictions are connected in series the mass flow is the same in each unless the gas is cooled to such an extent that condensation occurs. However, if condensation is avoided once the mass flow is determined, all that is required to compute the temperature of the entering gas is the measurement of the total and static pressures at the first constriction. The temperature may then be determined.

Pneumatic pyrometers have been used successfully to measure the temperature of exhaust gases from the combustion of hydrocarbons up to 1840°C (Ref. 198). It has also been used to measure temperature in rocket combustion chambers (Ref. 199) and as an in-flight instrument for measuring jet engine exhaust gases (Ref. 200). The dissociation effects at high gas temperatures complicate the determination of an effective specific heat ratio making this method of temperature measurement more difficult.

Another method of temperature measurements is concerned with microwave absorption and is based upon the principle that increased microwave continuation in a gas, e. g., a flame, will occur when thermally induced ionizations occur. Furthermore, the density of free electrons and therefore the attenuation created by this effect is functionally related to the absolute temperature of the gas (Ref. 201).

A system employing this technique would consist of a microwave transmitter and a receiver. The transmitter may consist of a 1000 cps modulated microwave X (3 cm) or K (1.25 cm) band generator followed by a high directivity antenna which may consist of a pyramidial horn followed by a lens to increase the directivity. The receiver may consist of an antenna lens combination similar to that of the transmitter. The received signal is rectified by a square can detector

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198 Simmons, F. S. and G. E. Glawe, Theory and Design of a Pneumatic Temperature Probe and Experimental Results In A High Temperature Gas Stream, NACA TN 3893

199 Trent, C. H., "Investigation of Combustion In Rocket Thrust Chambers", Industry and Engineering Chemicals, Vol. 48, April 1956

200 Havill, C. D. and L. S. Rolls, A Sonic-Flow Orfice Probe For The In-Flight Measurements of Temperature Profiles of a Jet Engine Exhaust With After-Burning, NACA TN 3714

201 Kuhns, Determination of Flame Temperature From 2000°K to 3000°K By Microwave Absorption, NACA TN 3254, 1954

amplified by a 100 cps amplifier which is followed by an indicator. The minimum spacing between the antennas is to be such as to avoid interaction between the two antennas. The flame is placed midway between the antennas. The temperature of the flame is measured by comparing the output of the receiver with and without the flame and relating the difference in the received signals to the flame temperature.

A number of approximations are normally necessary to relate the temperature to the equivalent conductivity of the flame medium. And again approximations are necessary to determine the effect of the finite size of the conductive flame, such that the accuracy of the temperature measurement is therefore limited. Accuracies of $\pm 60^{\circ}C$ have been reported in the temperature range 1600 to 2100°C. The upper limit of the instrument is that temperature where almost all the atoms are ionized. The lower temperature limit depends on the ability of the microwave receiver to detect small changes in received signals.

From standard works on acoustics we have relationships which provide a means of determining the temperature of a gas from sound velocity measurements, if other terms are known or reasonable values can be assumed or assigned. The methods of measuring the sonic velocity of a high frequency wave to determine gas temperature can be grouped into two categories. First category uses optical methods combine with photography. In this method, the wavelength λ of the sound waves in the gas are determined at a known and unknown temperature. These sound waves are generated by a crystal, driven by a known frequency oscillator. The unknown temperature may be calculated from the relation

$$\frac{\lambda_2}{\lambda_1} = \frac{C_2}{C_1} = \left(\frac{T_2}{T_1}\right)^{1/2} \qquad (2-67)$$

The second category consists of measuring the transit time of a transient acoustic signal across a gas path of a given length. Several other measurements referred to in the literature as sonic temperature measurements use waves caused by spark discharges and might better be considered shock wave measurements.

The use of the velocity of sound as a method of measuring temperature was suggested by A. M. Mayer in 1873 (Ref. 202) and subsequently by various investigators in the field. The following references suggest use of

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202 Mayer, A. M., Philosophical Magazine, Vol. 45 n 18, p. 1973

this technique in various applications: (Ref. 203, 204, 205, 206)

Some advantages of the sonic method are: It is inherently fast, so rapidly changing temperatures can be followed. The lag normally caused by the heat capacity of the thermometer element is absent. The measured temperature is not dependent on the properties of another material. The chief disadvantage of the technique is that point temperatures are not measured, but instead an average temperature over the path between transducers is obtained.

To measure high temperature with reasonable accuracy using the sonic method, consideration should be given to these factors:

1. Values for the molecular weight and specific heat ratios of gases will have to be known more accurately.
2. The gap length over which the sound wave travels may increase due to ablation of the probes.
3. Since the sound velocity increases with increasing temperature, the time needed for the sound wave to travel the distance between two probes becomes smaller.

2-11 VIBRATION AND SHOCK MEASUREMENTS

Vibration may be defined as a term relating oscillatory motion in a mechanical system. In the Glossary of Telemetry Transducer Terms (see Appendix II) vibration is defined as: motion due to a continuous change in in the magnitude of a given force which reverses its direction with time. Vibration

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203 Marlow, D. G., C. R. Nisewanger, and W. M. Cady, "A Method for the Instantaneous Measurement of Velocity and Temperature in High Speed Air Flow", Journal of Applied Physics, Vol. 20, 1949, p 771.

204 Barrett, E. W. and V. E. Suomi, "Preliminary Report on Temperature Measurement by Sonic Means", Journal of Meteorology, Vol. 6 n 4, August 1949.

205 Edels, H. and D. Whittaker, "The Determination of Arc Temperatures from Shock Velocities", Proc. of Royal Soc. (Series A), February-June 1957, pp 239-40.

206 Taylor, C. F., "Development of a Method for Measuring Gas Temperatures in the Combustion Chamber of an Internal Combustion Chamber of an Internal Combustion Engine", MIT, June 1953 - July 1954, ASTIA AD 41 455.

is generally interpreted as symmetrical or non-symmetrical fluctuations in the rate at which acceleration is applied to an object. And a closely related term "shock" is defined as: an abrubt change in applied energy. Shock is often considered a transient function of vibration. Terminology in this area can overlap as the period or function of time is considered. Oscillatory motion for several milliseconds may be considered shock.

Measurement and study of vibration and shock includes considerations of displacement, velocity, acceleration, rate of change acceleration (jerk), and frequencies. Vibration may be periodic, sometimes defined deterministic in that the variation with time is predictable from repeated past history; or random such that the parameters are not predictable from any recognized repeated pattern.

Newton's laws of motion clearly relate the vibration parameters, acceleration, displacement exciting force and mass involved. The fundamentals of acceleration measurements presented earlier deal with these basic relationship. This subject is treated in great detail in many texts and is the basis for derivations of relationships in translational and rotational motions. Mr. Ralph E. Blake, (Ref. 207) presents an excellent review of motion analysis fundamentals in Chapter 2, "Basic Vibration Theory" in Volume 1 of the Shock and Vibration Handbook.

Vibration measurement in practice becomes an analysis of a system whereby various forms of the basic laws of motion are duplicated electrically, by interpreting the analogies and choosing the more appropriate measurements desired. Displacement may be measured and if related to time define the parameters of vibration, velocity by differentiation, and double differentiation for acceleration. Similar velocity or acceleration may constitute the basic measurement employing integration or differentation to obtain other parameters. Thus the measuring device may be chosen for its ease and ability to obtain accurate results. Low frequency vibration may increase the difficulty of velocity or acceleration measurements and measurement of displacement may offer the greater advantage. Usually at the higher frequencies the excursion or displacement range becomes quite small and therefore more difficult to measure; and furthermore the frequency response of the displacement device may not be adequate. Acceleration of velocity pickups may then be the answer with integrating circuits or manipulation employed to arrive at the displacement parameter. However, acceleration, velocity and displacement are only correlated easily when the vibration measurement is a simple sinusoidal motion containing one frequency. The normal more

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207 C. M. Harris and C. E. Crede, Shock and Vibration Handbook, In Three Volumes, McGraw-Hill Book Co., Inc.

complex vibratory motion requires that data be analysed isolating each specific frequency or employ more exotic measurements and analysis.

The simplest vibratory system shown in Fig. 2-121 is called a single degree-of-freedom system, since a single mass, m , displaced in a constrained direction so that its change of position is fully described by the single quantity x. The degrees-of-freedom of a system indicate the number of independent parameters required to define the distance of all masses from their reference positions. A single mass, m , constrained to move only in x and y direction would be constitute a 2 degree-of-freedom system. A continuous system such as a beam, wherein infinitely thin cross-sectional slices represents each mass, is considered to have an infinite number of degrees-of-freedom.

If a mass is a system is displaced from its initial reference, then the force of displacement removed and the mass is allowed to vibrate free, without external acting forces, it is exhibiting free vibration. Forced vibration is the condition when a continuing force acts on the mass, or the foundation is under continual motion. The natural frequency is the free vibration frequency of a system and may be defined by

$$fn = \frac{1}{2\pi}\sqrt{\frac{kg}{W}} \qquad (2-68)$$

where

fn = natural frequency
k = spring constant
W = weight of rigid body
g = acceleration of gravity

The reciprocal of the natural frequency is the period or time interval of one complete cycle of sinusiodal oscillation.

Damping is defined as the dissipation of energy with time or distance. It is the characteristic, of the measuring device or the vibrational system, to resist continual or free vibration. In a simple vibration measuring device the damping is usually controlled, or specified to improve the performance of the device over a selected band of frequencies. The relationships of damping in simple harmonic systems are well defined in many text. Practical methods of damping use gases, liquids, resilient solids, magnetic fields and auxiliary mass or counter-vibration subsystems.

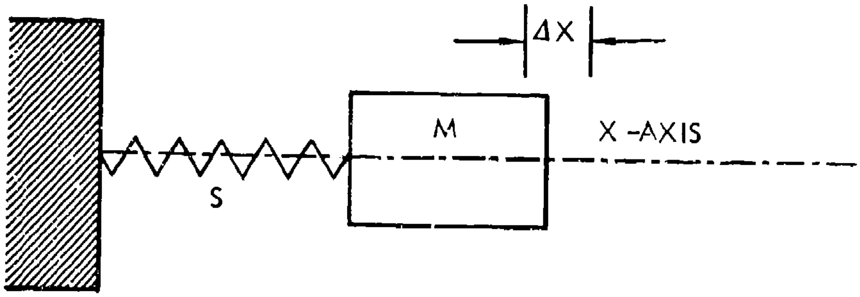

Figure 2-121 Single Degree-of-Freedom System

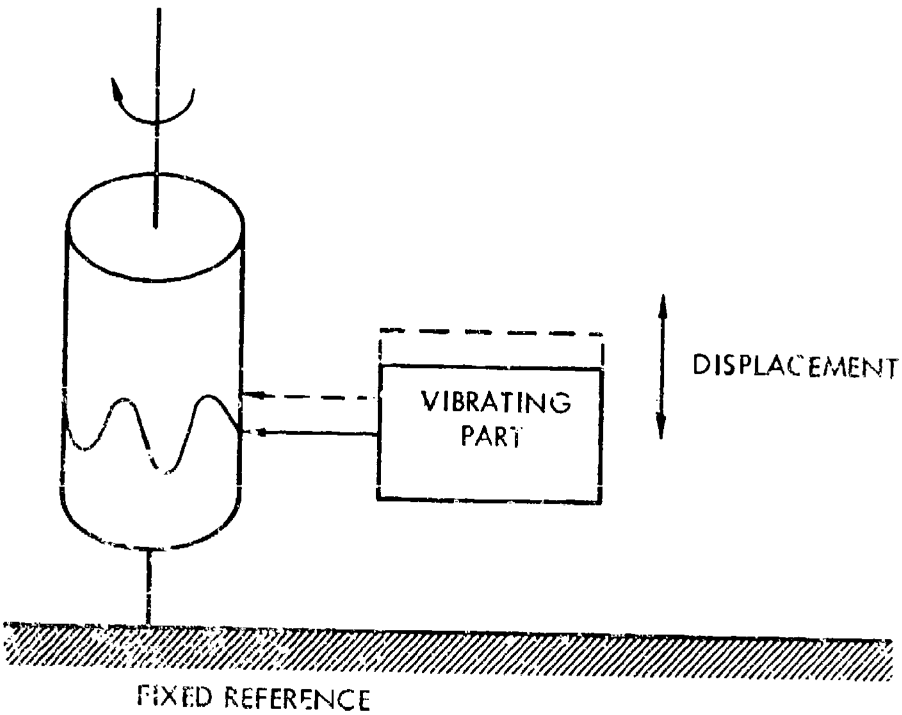

Figure 2-122 Fixed Reference Device

Vibration measuring instruments are of two general types, one in which the parameters are measured with reference to a fixed point in space, and the other related to the response of a mass-spring sustem. Fig. 2-122 illustrates a simple fixed reference device. Displacement is indicated by direct observation or use of displacement transducers monitoring the vibrating part. The mass-spring type instrument is attached to the vibrating member and the relative motion. Incorporated in the device is a displacement transducer to generate a signal relative to the mass versus case motion. Fig. 2-123 (a. - h.) illustrate principles of the various types of mass-spring type devices. They differ mainly by the type of displacement transducing element. The general types are: potentiometric, variable inductance, variable capacitance, unbonded strain elements, bonded strain gage, piezoelectric, piezoresistive, light modulated, and electrolytic. These type elements have previously been discussed and miscellaneous types are: electro-chemical, mechanoelectronic, optical interferometer, vibrating wire, tuning fork, gas-discharge, reflected wave interference, and servo accelerometer.

The piezoelectroc type vibration transducers are very widely used. They are of the self-generating type producing an electrical output signal in relation to the deformation of piezoelectric element. The piezoelectric element may be made of natural or synthetic crystals, ceramic materials (barium tetnate) and some-conductor materials. Types of devices may be classified as compressive or bending. Normally higher frequency response (natural frequencies to 100 kc) are obtainable when elements are in compression.

In chapter 16, Volume I, Shock and Vibration Handbook, (Ref. 208) A. I. Dranetz and A. W. Orlacclio present an electrical analog of the piezo-electric accelerometer. This is useful in deriving force displacement and motion relations and in calculating performance characteristics of a measuring system.

Piezoelectric transducers are usually small and lightweight (1 gram to several ounces). Larger units may have greater sensitivity or lower frequency response incorporating several elements in a system arrangement to enhance a particular function. Packaging and mounting are varied to suit application. Prime importance, of course, is the ability of the device to respond to the vibrating member being measured and therefore mounting arrangements from studs to epoxy cemented areas make up an appreciable portion of the physical design of the vibration instrument.

Electrical characteristics of the piezoelectric transducer are concerned with output signal. The sensitivity (output per unit of measured parameter) may be expressed as a voltage or charge sensitivity. Units are usually

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208 Same as Reference 207

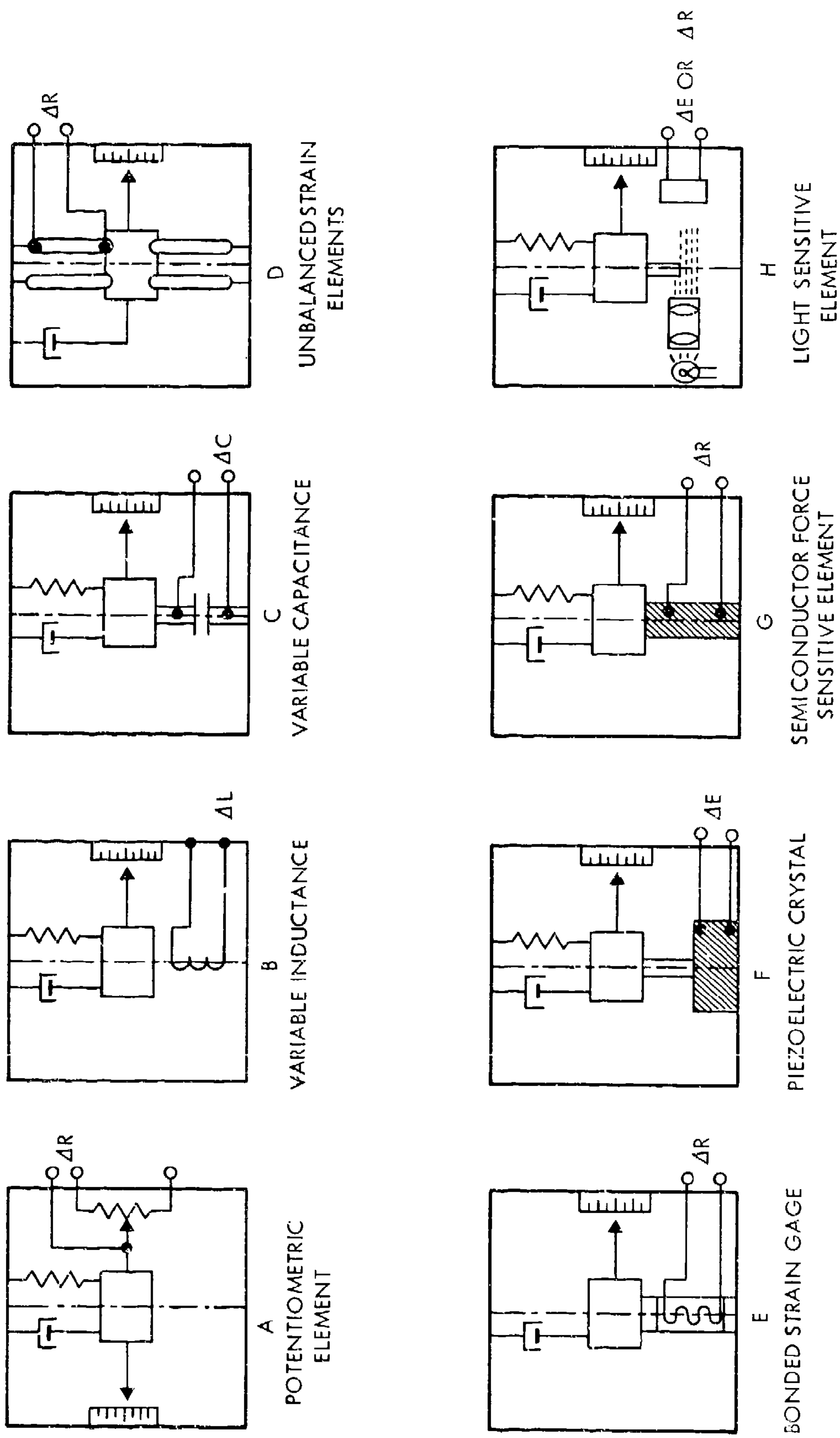

Figure 2-123 Mass-Spring Devices Employing Various Displacement Indicating Elements

millivolts per g or coulombs per g, where acceleration and time relate vibrational information. Typical sensitivity values range from 5 to 125 mv/g with load of 20 k to several 100 megohms (some require electrometer type amplifiers). The output impedance may indicate the low frequency characteristics of the device. The resistance and shunt capacitance of the transducer and the input resistance of the signal conditioner result in a time constant limiting the low frequency response. High input impedance amplifiers are usually necessary and with the great advancement in solid state microminiaturization many vibration pickups include output amplifiers. The high frequency response depends primarily on the natural frequency and the damping employed. Commercially available transducers employ damping ratios such that vibrational frequencies of .2 to .7 of the natural frequency may be followed with 5% or less variation in sensitivity. A virtually undamped system may operate at frequencies up to about .2 the natural frequency with approximately 5% variation in sensitivity (Ref. 209). Transverse sensitivity is the characteristic of the device to generate an output signal when acted on by force or acceleration in a plane other than the plane of motion being measured. This characteristic is normally specified in percent of maximum sensitivity. Typical values for transverse sensitivity are 1% to 10%.

The piezoelectric transducer normally has a wide acceleration range of operation. Typical units may operate from 0.02 g to 1000 g. Upper limits are usually determined by calibration unless maximum g value is dependent upon known physical limitations of case or mounting fixture.

Temperature effects on piezoelectric transducers are largely dependent on the piezoelectric element and of course, the packaging for any beneficial cooling at the elevated temperatures. Instruments are available for vibration measurements at ambient temperatures from -300°F to over 500°F maintaining ±5% sensitivity variations. The charge sensitivity and capacitance of piezoelectric element materials are temperature dependent. Thus voltage sensitivity and frequency response can be related to temperature changes for the various materials. In particular cases the damping characteristic may be temperature dependent at extended temperature ranges.

High intensity sound environments may effect the characteristics of piezoelectric vibration transducers. Peak outputs will result at the resonant frequency of the seismic system. Damping will lower this output. One type vibration pickup produced a signal equal to 10 g acceleration in presence of 170 db acoustic noise and approximately a 1 g signal at 150 db noise and a 0.1 g signal at 130 db noise.

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209 Same as Reference 207

The electrochemical types include the electrolytic potentiometers and other devices using electrolytic cell, where ions in the solution carry the electric charge. They require low power and have essentially no moving parts. Disadvantages of some types include temperature sensitivity, frequency limit atoms, and possivility of contamination of cells. Solion (Ref. 210 and 211) transducer produce a signal as shock or vibration induces movement of the electrolyte, which disturbs an ion concentration, established by an external voltage source, around the electrodes of the cell. This causes a change in current flow in the external circuit. Solion transducers are low frequency devices (0 to 200 cps) and temper ture dependent operating in the range +28°F to +90°F. Temperature compensation is usually employed.

The porous disc transducer (Ref. 212 and 213) is another electrochemical type based on an electrokinetic phenomenon that occurs when a polar liquid is forced through a porous disc. When the liquid flows through the pores, a "streaming" voltage potential is generated across the disc, in phase with and proportional to the differential pressure across the faces of the disc. The electro-osmotic cell uses this principle. Polar liquids used are water, methanol, and acetonitride. The frequency response of devices of this type may be flat within ±3 db from 3 cps to 60,000 cps (Ref. 214). Sensitivities depend on cell liquids and column length, ranging from a few mv/g to 500 mv/g. The operating temperature range is determined by the boiling and freezing points of the polar liquid. High impedance loads may not require temperature compensation, but for load impedances comparable to the cell impedance external circuit compensation is required. The operating characteristics of this type transducer may be made to vary over extremely wide range by selection of working fluids.

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210 Hurd, R. M., R. N. Land and H. B. Reed, "Solion-principles of Electrochemistry and Low Power Electrochemical Devices", U. S. Naval Ordnance Laboratory, 1957

211 "Solion For Industry", Electronic Products Engineering Bulletin, National Carbon Co., 1957

212 Hardway, Jr., E. V., Instruments, 1953

213 "Electro Kinetic Measurement of Dynamic Pressures", CEC Recordings, November, December 1956

214 Bulletins 1600 and 16002, Consolidated Electrodynamics Corp.

The mercury-electrolyte transducer is still another electrochemical type. Fig. 2-124 shows a basic type whereby alternate slugs of mercury and electrolyte solution, such as potassium iodide or sodium chloride are contained in a capillary tube. A voltage is generated between the electrodes when the tube is shaken, causing relative motion between the capillary and mercury-electrolyte system. This phenomenon is called the Latour effect (Ref. 215) or V-effect II (Ref. 216). The output voltage is a function of the number and length of slugs, vibration amplitude and frequency. These devices have high sensitivity combined with high power output, may be self-generating, low internal impedance, and can be quite small and light weight. Disadvantages include temperature sensitivity and sensitivity to shock damage.

The mechanoelectronic type transducers employ the application of an electron tube with variable relative spacing of its elements, such that a change of current or voltage is indicated at the output proportional to relative movement of elements. Very small displacement can be sensed, the moving elements can be quite small, frequency response can be high and the many applications of electron tubes and associated circuits may be employed in more complex transducers. There are problems of drift and zero-shift which must be compensated and the difficulty to fabricate vaccum sealed shell through which displacement or vibration must be transferred. Acceleration, vibration, displacement and pressure sensing transducers of this type have been developed. (Ref. 217, 218, 219)

Optical electronic transducer types include many types, but essentially measure displacement without requiring contact with moving element, sensing the reflection or transmission of light controlled or modulated by the moving element being measured. The Optron Corporation (Ref. 220) has a system

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215 Fain, W. W., S. L. Brown and A. E. Lockenvitz, Journal of Acoustical Society of America, 1957

216 Podalsky, B. G. Kuschevics, and J. L. Revers, Journal of Applied Physics, 1957

217 Olson, H. F., Journal of Acoustical Society of America, 1947

218 RCA Tube Manual, Radio Corporation of America

219 Ramberg, W., Electrical Engineering, 1947

220 "Optron, Displacement Follower", Optron Corp.

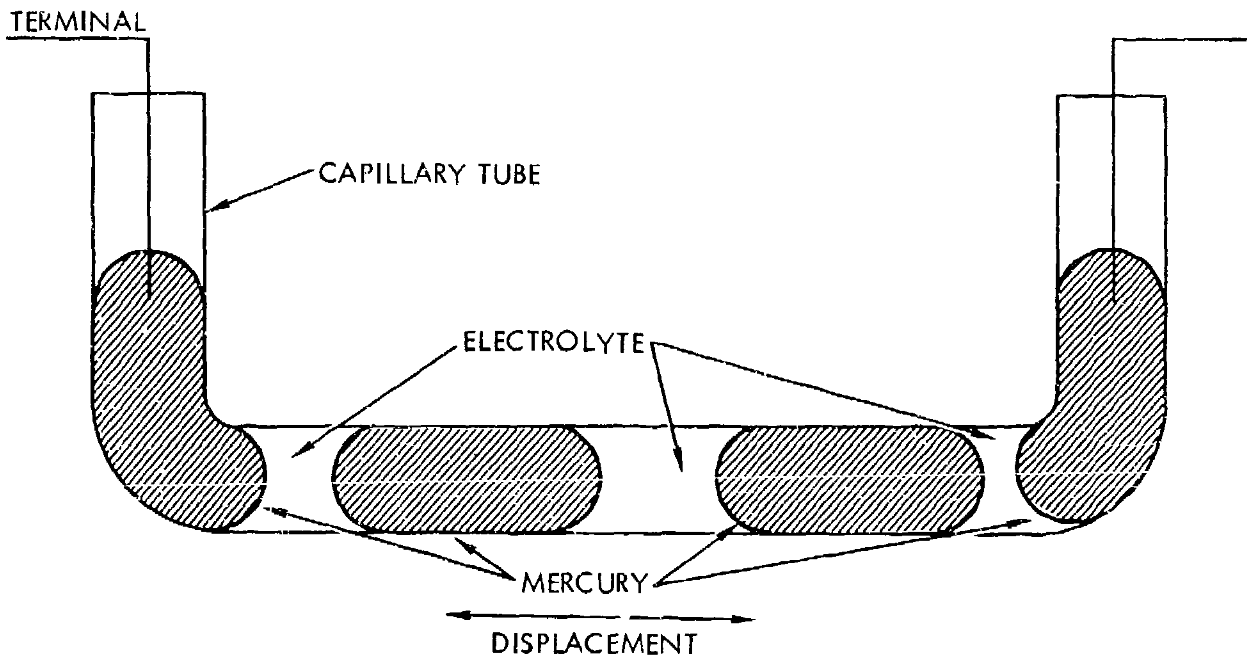

Figure 2-124 Mercury - Electrolyte Vibration Transducer

for vibration measurements that uses a controlled spot from a special purpose cathode ray tube focused through a lens system onto a reflected area of a vibrating member to be measured. A photocell is placed to receive the reflected light and the photocell output drives a servo amplifier which controls the bias to the cathode ray tube. The control loop is adjusted so that when no light is reflected the cathode ray tube spot is directed downward and when reflected light is received it is directed upward. Thus, the spot is held on the edge of the reflected area. When the member is displaced or vibrated the edge of the reflected area of course follows follows and the projected spot will track the displacement. The electrical signal driving the spot is proportional to the displacement. Full scale displacement ranges of 0.001 inch to 10 inches are available with frequency response to 10,000 cps. Accuracies of 0.1% are attainable.

Another type optical electronic transducer used in vibration measurement is the optical interferometer. (Ref. 221 and 222) A beam of light from a monochromatic source is directed onto a half silvered mirror which reflects part of the beam along one path and transmit part along another path. These beams are reflected by optically flat mirrors to recombine in a viewing telescope. One of the optical falt mirrors is fixed and the other permitted to move along the axis of the light beam, its movement actuated by vibrating member to be measured. If the effective length of both light paths are equal the recombined images will result in a light beam of the same intensity as the original beam. If however the movable mirror is displaced such that the effective light path from one mirror is a half wave length longer than that from the other mirror, the recombined image will produce a dark field. Displacements as low as 4 microinches can be detected using a monochromatic light source of 5,641 angstroms (mercury-vapor light with filter). The interferometer is used for calibration of vibration measurements in the 30 to 20,000 cps range.

The vibrating-wire transducer consists of a taut wire supported between two knife edges, an oscillator driver and a detector. The natural frequency of the wire varies with length and tension. The motion being measured is coupled to one support causing the tension of the wire to vary in realtion to the motion. The oscillator driver is adjusted to operate at the natural frequency of the taut wire indicated by a maximum output of detector. Detector output is amplified and fed back to control the frequency of the oscillator driver so that as the tension changes, the oscillator driver changes frequency to maintain operation at the wires resonant frequency. The output of the control circuit or a detected change in frequency

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221 Hunton, R. D., A. Weis and W. Smith, Journal of Optical Society of America, 1954

222 Edelman, S., E. Jones and E. R. Smith, Journal of Acoustical Society of America, 1955

may be used as the signal output denoting measrued motion. Displacement, vibration, pressure, strain and torque type devices have been developed using this principle. (Ref. 223, 224)

If a gas discharge type tube containing two electrodes is placed in a radio frequency electric field, a dc voltage will be developed between the electrodes, when the electrodes are not symmetrically located in the field. Sensitivities as high as 0.05 volts/microinch have been attained with dc outputs as high as 60 volts.

Reflected wave type vibration measurement systems consist of a transmitter and receiver or special sensing device. In one type a microwave frequency is transmitted along a wave guide, with open and toward the vibrating surface being measured. By tuning the wave guide and adjusting the frequency, a standing wave pattern can be established that is very sensitive to the portion of the reflecting surface being vibrated. The demodulated output of the VSWR indicator is proportional to the motion of the surface being measured. Displacements less than 1 microinch and at frequencies to 1000,000 cps have measured using this type technique. (Ref. 225)

A transmitted microwave beamed toward a vibrating surface will reflect a wave phase-shift modulated in proportion to the vibration amplitude and frequency of the reflected surface. At frequencies around 1 cm wavelength, maximum displacement range of 1 wavelength with 1% accuracy and resolution to 0.1 microinch has been measured. (Ref. 226)

Power from ultrasonic transponders reflected by a vibrating surface has been measured and the amount and phase related to the vibrating motion. The Doppler-frequency shift in an ultrasonic carrier reflected from a vibrating surface from the transmitter/receiver, but only on the velocity of the motion of the reflecting surface. (Ref. 227 A)

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223 "Remote Measurement and Control With Vibrating Wire Instrument", Electronics, June 1945.

224 Allen, W. H., U. S. Pat. 2,725,492; Reviewed in Journal of Acoustical Society of America, 1956.

225 Cohn, G. I., and B. Ebstein, "A Microwave Non-Contacting Tracing Technique For Automatic Contour-Following Machines", Proc. of National Electronics Conference, Vol. 12, 1956.

226 Steward, Chandler, "Proposed Massless Remote Vibration Pickup", Journal of Acoustical Society of America, 1958.

227 A Hardy, H. C., H. H. Hall, D. B. Callaway, and D. J. Schorer, Journal of Acoustical Society of America, 1955.

Servo type transducer systems are a type normally associated with lower frequencies (below 100 cps) but may be made very sensitive, accurate and stable. Characteristics of transducing element are electronically controlled or modified by servo loop control and although this type usually infers a more complex measurement system, it offers a point or connection to obtain signal indication and develop a control signal. The control signal is usually of the error type where the measured value is compared with a pre-planned, standard or programmed signal and further used in the loop to compensate and improve the measuring system.

2-12 MEASUREMENT OF THRUST (Ref. 227 B)

Precise knowledge and control of thrust levels is of prime concern is missile and space probe systems. Accurate and independent measurements of thrust and acceleration provide data for precise space maneuvers as well as flight performance monitoring.

There are two general categories of in-flight thrust measurements. These are direct, where use is made of vehicle motion or where actual forces are measured; and parametric, in which motor parameters are measured and used in thrust calculations.

a. The in-flight thrust of a vehicle may be determined by measuring the characteristics of its motion as devined by the terms on the right hand side of the following dynamic equation:

$$\vec{T} = M(\ddot{\vec{r}} - \vec{g}) - \sum_{i=1}^{n} \vec{F}_i \qquad (2\text{-}69)$$

where

$\vec{T}$ = the vehicle thrust vector to be determined
M = the total instantaneous mass of the vehicle
$\ddot{\vec{r}}$ = the total inertial acceleration vector of the vehicle
$\vec{g}$ = local gravitational acceleration vector
$\vec{F}_i$ = the i th external force vector acting on the vehicle
$(\cdot)$ = designation of differentiation with respect to time
$\sum_{i=1}^{n}$ = designation of the summation from i=1 to i=n (a number)

Major emphasis is given to various methods for measuring the vehicle acceleration $\ddot{\vec{r}}$.

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227 B Martin, T., Scharres, E. H., Sperry, W. and Zimmerman, F. J., "Thrust Measuring Techniques," WADD TR60-488, Armour Research Foundation of Illinois Institute of Technology, July 1960. AD253148

1. Accelerometer Technique

This technique makes use of accelerometers mounted on a gyro stabilized platform to obtain vehicle acceleration conditions relative to a non-rotating, space oriented, coordinate frame of reference. In general, three accelerometers will be needed and must be mounted such that the output of each corresponds to the acceleration components along each of the three platform oriented coordinate axes. Combining this information with that obtained from the external force sensors and a mass flow meters, a computer can be mechanized to solve for both the magnitude and direction of the vehicle thrust. See Appendix for further details of this technique and a discussion of signigicant external forces effecting thrust calculations.

Advantages in this thrust determination technique are: no special measurement of gravitational acceleration is required, it makes use of a number of components that are already included in the guidance system of vehicles that most likely would require an accurate knowledge of the thrust, and it is a passive technique requiring no external reference information. It may be necessary, however, to make either continuous or periodic celestial fixes to gyro drifting, thereby tempering the latter advantage somewhat.

The disadvantages in the system are (1) the problem involved in adequately determining the aerodynamic forces acting on the vehicle and (2) the problem of designing special mass flow meters for the various types of propulsion unit configurations.

Other methods employing vehicle acceleration concern acceleration measurement using external references. For such measurements to be useful in determining vehicle thrust, it is essential that they provide information that is compatible to the reference frame in which the thrust equation is valid. A gyro stabilized platform aboard the space vehicle is normally be used and by preset orientation, a coordinate system is established, referenced to the earth or a similar planet near the flight path. In remote regions of flight it may become necessary to establish one's own external reference. An example of this would be the release of an object from the vehicle at some time, prior to an anticipated thrust maneuver, and the continuous tracking of its motion relative to the vehicle, using suitable tracking devices aboard the vehicle.

2. Combined Accelerometer - Force Transducer

The object of this technique is to combine the best properties in each approach to eliminate some of the troublesome variables which are present when considering an individual method. The variables of drag, when

operating within an atmosphere, and changing mass, due to the discharge of fuel, complicate thrust calculations considerably. Values for drag can be determined through many additional measurements, air density, angle of attack, velocity, frontal area, drag coefficient, etc., with many inter-relations. Careful examination of the particular application should allow approximation of drag with a minimum of measurements, realizing that a certain sacrifice in accuracy results. However, the usual case in further analysis makes very clear and need for thrust measurements independent of drag or in which drag is felt directly eliminating the need for separate determination.

The changing mass problem or difficulty in measurement of instantaneous mass, forces one to keep track of the departure of each portion of mass from the vehicle. The many variables involved in such an attempt, with instruments, now available or in development, indicate undersirable or impractical inaccuracies.

The combined accelerometer-force transducer technique is independent of drag and changing mass. It will work equally well within and without the atmosphere and is unaffected by varying gravitational fields. It depends only on precise measurement of acceleration (possible with the present state-of-the-art) and precise measurement of the force between the motor and the vehicle. It is especially well suited to liquid propellant engines; however, it is applicable to any motor. An additional feature of the system is that it will measure thrust direction as well as magnitude whether directional changes are obtained from vectoring systems or gymballed nozzles or whole motors.

An interesting application example based on data from V-2 rocket system is discussed in the Appendix. Also thrust equations for liquid propellant and solid propellant systems are presented.

In brief, the mass of the vehicle is separated into mass M. of the rocket motor and its contained fuel, which is assumed constant during powered flight phase, and mass M_2, consisting of the remaining portion of the vehicle (payload, fuel, instrumentation, etc.). See Figs. 2-125 and 2-126. The rocket motor thrust accelerates both masses equally and a proportional amount is transmitted from the motor through the mounting brackets to propel M_2. A force transducer measures the compression load for force (P) in the mounting brackets and thus:

$$T = M_1 a + P \tag{2-70}$$

Then in atmosphere the total drag force acting on the vehicle is assumed to act

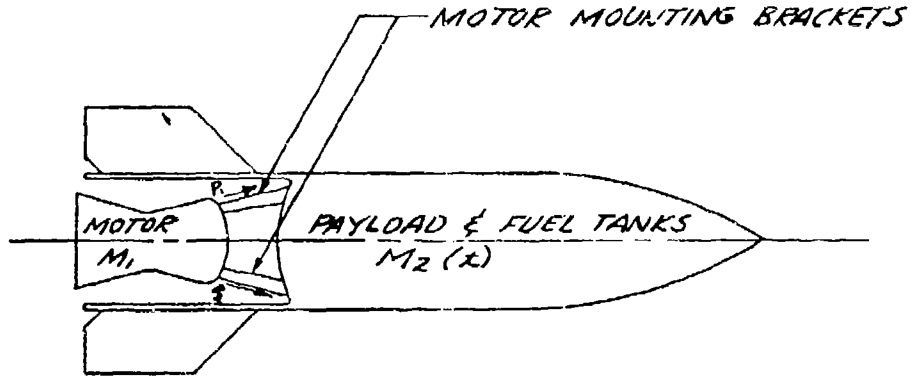

Fig. 2-125 Separation of Masses Consideration for Liquid Propellant Systems

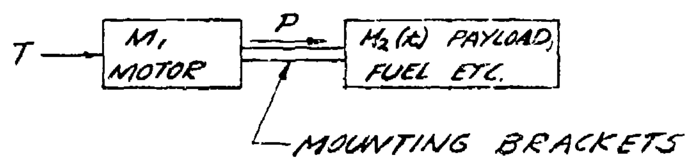

Fig. 2-126 Simplified One-Dimensional Example

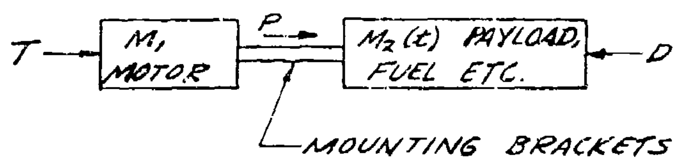

Fig. 2-127 One-Dimensional Example with Drag Force D

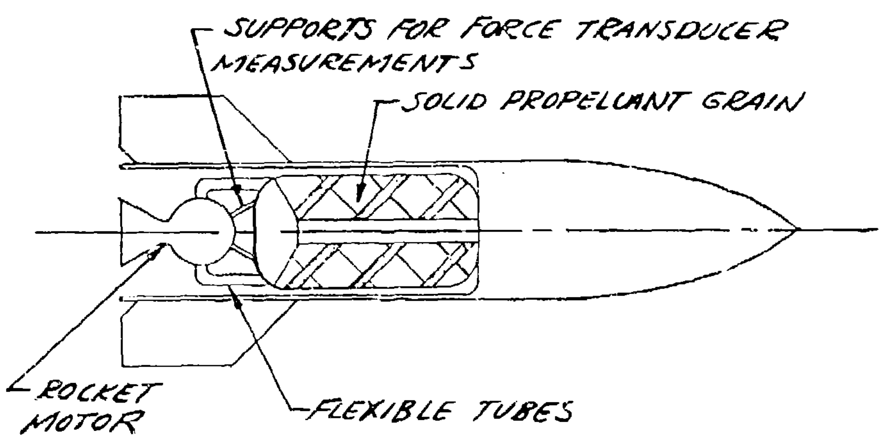

Fig. 2-128 Force Transducer-Accelerometer Technique Applied to Solid Propellant Rocket Motor

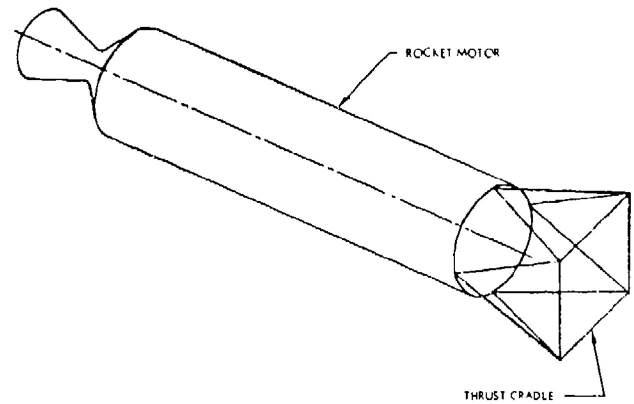

Fig. 2-129 Diagram of Rocket Engine and Thrust Cradle

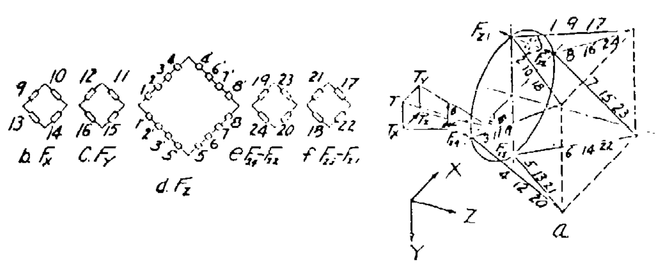

FIGURE	MEASURES COMPONENTS	CANCELS EFFECTS DUE TO	ALLOWS DEFLECTION IN	PREVENTS DEFLECTION IN	SENSITIVE TO ACCELERATION IN
b	F_x	PITCH, ROLL	Y	X, Z, PITCH, ROLL	X, YAW
c	F_y	YAW, ROLL	X	Y, Z, YAW, ROLL	Y, PITCH
d	F_z	X, Y, PITCH, YAW, ROLL		X, Y, Z, PITCH, YAW, ROLL	Z
e	$F_{24} - F_{22}$	Y, Z, PITCH, ROLL	X	Y, Z, YAW, ROLL	YAW
f	$F_{23} - F_{21}$	X, Z, YAW, ROLL	Y	X, Z, PITCH, ROLL	PITCH

Fig. 2-130 Mechanical Arrangement of Force Sensors

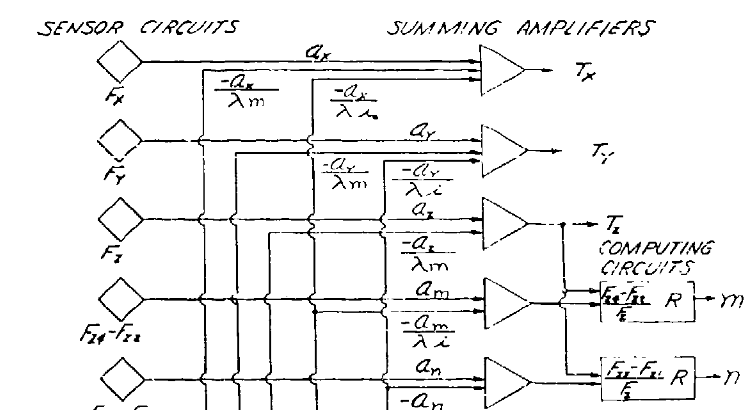

Fig. 2-131 Computer for Direct Thrust Measurement System

only on M_2 and again the thrust determination is independent of drag measurement. If the load or force (P) and the acceleration (a) are sensed continuously by appropriate instrumentation, it is then possible to calculate thrust (T) knowing only mass of motor (M_1).

In solid propellant systems where fuel is part of the motor, mass M_1 may be interpreted as the mass of the nozzle and the force measuring transducer placed such that force (P) is actually that force produced in the nozzle acting on mass M_2, in this case, the reminder of the rocket motor, solid propellent fuel and payload. (See Fig. 2-128) A careful analysis of the production of thrust in the nozzle is necessary to insure measurement of valid force (P) for use in thrust calculations. See Appendix for further details.

3. Direct Method - Force Measurements

The bonded resistance strain gage has had wide-spread use for thrust component measurement in static test stands for engines and vehicles. A number of these force sensors can be integrated both mechanically and electrically into complete thrust measuring systems. A number of such systems monitor the forces produced at the attachments of the motor to the vehicle. Fig. 2-129 shows diagram of rocket engine and thrust cradle. The accompanying Fig. 2-130 indicates mechanical arrangement of force sensors and force vectors measured. Block diagram in Fig. 2-131 indicates computer logic yielding direct thrust measurement.

These systems are sensitive to acceleration forces in the directions of thrust components as well as in the pitch, yaw, and roll axes. The motor and its suspension is, in a sense, a large triaxial accelerometer and hence will sense the acceleration forces on the vehicle.

Accelerometers could be used to sense these accelerations and these signals used to cancel out the undesirable forces in the system. To accomplish this cancellation dynamically it is necessary to match very closely the dynamic characteristics of the motor suspension system so that the compensation is effective at all times.

A method of accomplishing the compensation which is related to the method of using accelerometers is to construct a dynamically similar model of the rocket motor and its suspension. This model is then placed in the vehicle and is subjected directly to all of the forces except the thrust. Thus, measurements can be made on the model to compensate for the components of thrust which are sensitive to the inertial and gravitational forces.

b. Determination of Thrust By Parametric Methods

1. One of the general methods available for thrust determination incorporated the use of engine parameters. If a satisfactory means can be found for measuring the various parameters which can be used to determine thrust, some important advantages may be gained. Namely, many of the available parameters are independent of the environment, or the effects of the environment are felt directly in the measurement making separate measurement of individual environment properties unnecessary. This can be a decided advantage when operation both within and without the sensible atmosphere is anticipated. Additionally, some monitoring of engine parameters will no doubt be necessary for such things as safety and determination of fuel used to arrive at instantaneous vehicle weight. Output from these measurements can be used to arrive at rocket thrust, obviating the need for a separate measuring system.

Among the many engine parameters which are available, the following appear to offer the greatest potential for thrust determinations:

Fuel flow rate ($\dot{m}$)
Specific impulse of the propellant (I_{sp})
Exhaust velocity of the discharge gas (V_e)
Rocket motor chamber pressure (P_c)
Characteristic nozzle dimensions (A_t and A_e)
Chamber temperature (T_c)

The preceding list contains the basic engine parameters which can be used to determine the thrust of the rocket. There are a number of other parameters available such as temperature at the throat or exit of the nozzle, pressure in the same locations and chemical and physical properties of the propellant. Through suitable relationships the latter can be used to determine the basic parameters which, in turn, can be used to determine thrust. These parameters appear to be more important for thrust determination schemes since they are generally less extreme and more amenable to measurement. However, there is a greater possibility that some of these parameters will introduce larger errors in the thrust determination because of less sensitivity to perturbations.

The many forms of the thrust equation must be analyzed for the particular application to determine if it is practical to measure, to the required accuracy, the determining parameters. For example the simplest form of thrust equation may be:

$$T = \dot{m}\, Isp \qquad (2\text{-}71)$$

where

$\dot{m}$ = weight flow rate lb/sec
Isp = specific impulse of the propellant

To determine thrust from this equation it is only necessary to measure two parameters, and if it can be assumed that Isp is a relatively predictable term for varying altitudes for a given propellant and nozzle configuration then only mass flow rate $\dot{m}$ must be measured. This is a very important parameter in rocket systems instrumentation and the degrees of accuracy and ease of measurement varies greatly with specific vehicles and application of vehicles. In liquid fuel types the easiest approach may be measurement of a volumetric flow rate of fuel and oxidizer before entrance into the combustion chamber using standard flowmeter in the propellant feed lines. Temperature compensation is necessary in the mass flow rate calculation and inaccuracies are likely due to temperature transients and lag in sensing. Probably the best accuracy to be expected in mass flow rate measurement using flowmeters is 2 to 5%.

There are many schemes for measuring mass flow rate, such as: tracer introduction and detection; use of thermodynamic relations using known cross-sectional areas, thermodynamic coefficients, pressures and temperatures; measurement of surface burning rate of solid propellent; or depletion rate of fuel. There are advantages, disadvantages and degrees of inaccuracy associated with each. By-products of the many other normal and special measurements made in a system may be correlated to improve or compensate inaccuracies.

The term Isp, specific impulse, in our simple thrust equation is the impulse, or pound-seconds available from the combustion of one pound of propellant in a rocket motor. Although theoretical determination is readily available using known equations, its value is limited in that in practical systems the theoretical maximum is never achieved. Analysis of Isp in practice reveals other relations in the determination of Isp using measurements of back pressure into which nozzle is exhausting, true an exit area of nozzle (not always constant as for mechanical exit area), and exhaust velocity of gas at nozzle exit.

Other forms of the thrust equation which suggest use of other parameters are:

$$T = \lambda \dot{m} \ Ve + (Pe - Pa) \ Ae \qquad (2\text{-}72)$$

where

T = thrust
$\dot{m}$ = mass rate of discharge
Ve = true velocity of the exhaust at exit
Pe = pressure of exhaust at exit
Pa = external pressure
= factor correcting for divergence of the nozzle at the exit.

$$T = Dd\ At\ Pc\ Isp \tag{2-73}$$

where

Dc = discharge coefficient
At = area of nozzle throat
Pc = chamber pressure
Isp = specific impulse

$$T = \frac{At\ Pc\ Isp\ g}{C*} \tag{2-74}$$

where

$\frac{g}{C*}$ is substituted for Cd

and

g = gravitational constant
$C*$ = characteristic exhaust velocity

$$T = Cf\ At\ Pc \tag{2-75}$$

where

Cf is called the thrust coefficient

and

$$Cf = \sqrt{\frac{2K^2}{K-1}\left(\frac{2}{K+1}\right)^{\frac{K+1}{K-1}}\left[1-\left(\frac{P_2}{P_1}\right)\right]^{\frac{K-1}{K}}} + \frac{P_2 - P_3}{P_1} \cdot \frac{A_2}{At} \tag{2-76}$$

using inlet pressure and area and exhaust pressure and area. This thermodynamic determination is based on a number of simplifying and error-introducing assumptions and C_f can more successfully be determined on the thrust test stand, since it is a characteristic of a given nozzle.

2. Indirect Parameter Measurement

There are many phenomena associated with rocket motor performance, that may be utilized in determining thrust measurements. Much investigation is going on to determine practical relations and useful measurement technique based on optical, infrared, and ultraviolet radiation and electromagnetic attenuation.

Fig. 2-132 and 2-133 show block diagram and relationship of possible use of electromagnetic attenuation technique. The transmitter and receiver may be mounted near the rockets exhaust directing their antennas rearward. Adjustable reflectors are provided to direct transmittal signal through the exhaust plume and back to the receiver.

The field of magnetohydrodynamics suggests another technique involving the interaction of a moving conductive gas (the rocket exhaust) and an applied magnetic field, inducing an emf proportional to the gas velocity and the magnetic flux. (Ref. 228)

Analysis of shock waves in rocket exhaust yield thrust direction information and use of an optical sensor might provide a practical parameter measurement.

Study of visible flame of the rocket exhaust yields many relations concerning nozzle geometry, the degree of under-expansion, the atmospheric pressure, chemical composition, vehicle velocity and aerodynamic vehicle configurations near the nozzle. Flame length may be related to the thrust produced.

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228 Sears, W. R., "Magnetohydrodynamic Effects in Aerodynamic Flows", ARS Journal, Vol. 29, No. 6, June 1959

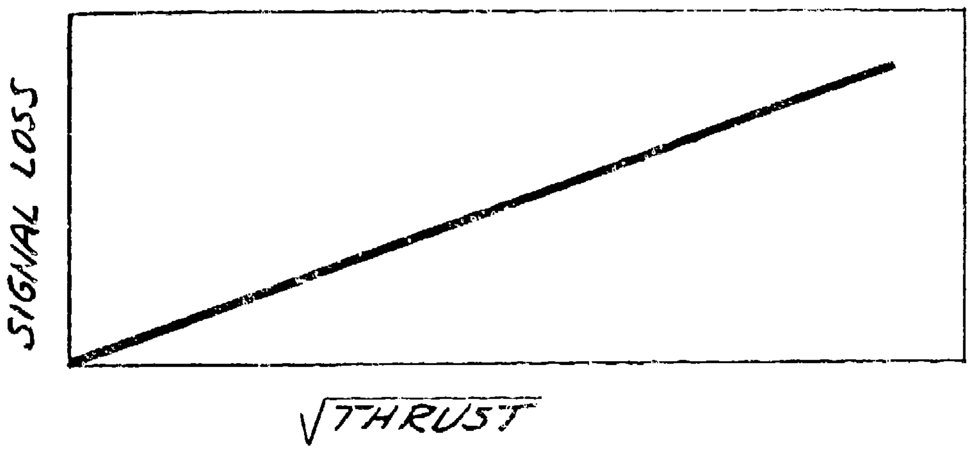

Fig. 2-132 Electromagnetic Attenuation/Thrust Relationship

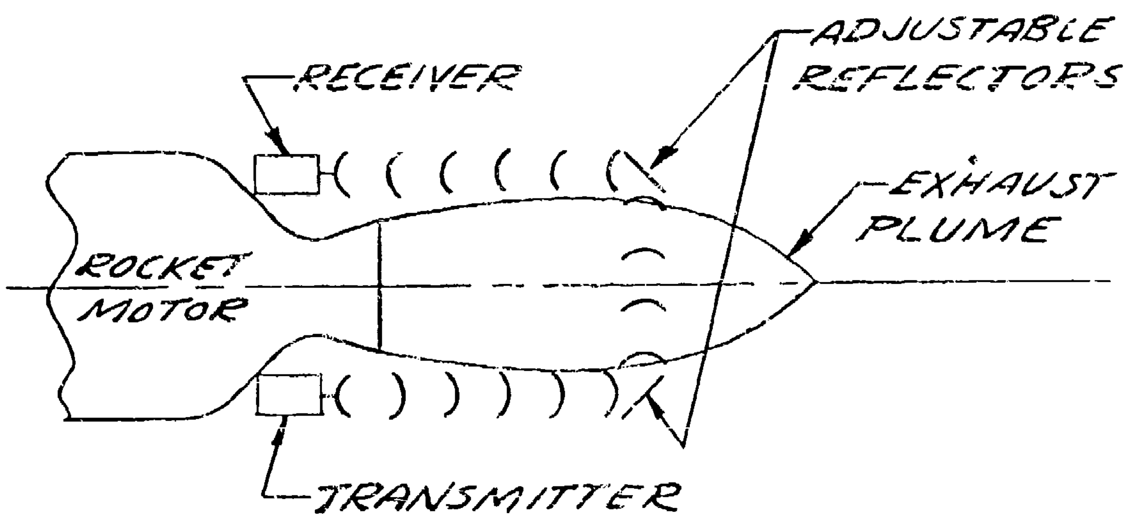

Fig. 2-133 Diagram of Electromagnetic Attenuation Technique of Thrust Measurement

The study of the relationship of noise to jet-stream characteristics, (Ref. 229, 230, 231, 232) initiated principally because of noise annoyance created by jet aircraft and concerning acoustical fatigue problems has revealed a qualitative noise and nozzle exit velocity relationship. Since thrust is also related to velocity an acoustical method of thrust measurement is strongly suggested. Only limited work has been performed along this direction but with availability of high temperature acoustical pressure measuring probes this method may offer more promise.

c. Advanced Propulsion System

Thrust measuring requirements and methods concerned with some of the more exotic propulsion systems indicate emphasis on direct thrust measurement techniques. Inter-relations and inaccuracies involved in any simplification are greatly enhanced in employing parametric methods in ion and plasma propulsion systems. In nuclear propulsion systems parameter measurement devices are subjected to extreme environmental conditions as well as the equation for thrust becoming more involved.

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229 Lighthill, M. J., "On Sound Generated Aerodynamically, I. General Theory", Proceeding of the Royal Society (London), Sec. A, 211, 1107, March 20 1954, p. 564.

230 Lighthill, M. J., "On Sound Generated Aerodynamically, II. Turbulence as a Source of Sound", Proceeding of the Royal Society (London), A222, I, 1954.

231 Callaghan, E. E., and W. D. Coles, "Far Noise Field of Air Jets and Jet Engines", NACA Report 1329, 1957.

232 Howes, W. L., E. E. Callaghan, W. D. Coles, and H. R. Mull, "Near-Noise Field of a Jet Engine Exhaust", NACA Report 1338, 1957.

NASA Photo No. 62 - MA6 - 94

Fig. 2-134 Astronaut John H. Glenn, Jr. undergoes last minute medical checks before MA-6 launch.

2-13 BIO-INSTRUMENTATION

a. Introduction

Bio-Instrumentation has experienced a rapid growth since World War II. The environments experienced and physical performance demanded of air crews have changed with every advancement into the space age. Manned space flight and the now present race-to-the-moon has focused attention on physiological function and life support measurements to insure man's safety and optimum performance during travels into new and unknown environments.

Bio-experiments with animals and man concerned with flight tests have been conducted with ever increasing emphasis since World War II. Sputnik II launched November 3, 1957 carried test animal "Laika" (a dog) instrumented for temperature measurements and effects of pressure. Discoverer III, launched June 3, 1959, carried four black mice in a re-entry capsule. Sputnik IV launched May 14, 1960 carried a "dummy" instrumented space man. The Russians launched a 5-ton spacecraft December 1, 1960 carrying two dogs, other animals and biological specimens. Another similar Russian craft with one dog was launched March 9, 1961. The United States Discoverer XVIII capsule contained human cells and was successfully retrieved Dec 10, 1960. The MR-2 space vehicle carried a 37-lb. chimp named "Ham" to a peak velocity of 5800 mph and on re-entry experienced 14G forces.

A major step came on April 12, 1961 when Yuri Gagarin made the first orbital space flight in the 5-ton spaceship Vostok. Shortly, thereafter, on May 5, U. S. Astronaut Alan Shepard traveled 115 miles into space and 302 miles out to sea in a 15 minute Mercury-Redstone flight. Then again on July 21, 1961 U. S. Astronaut Virgil Grissom rode a Mercury capsule to a 118 mile altitude and 303 miles out in the Atlantic Ocean. Then on August 6, 1961 Major German Titov traveled 17-plus circuits of the globe in space ship Vostok II. His flight lasted 25 hours and 18 minutes and of prime interest was the report of some air-sickness due to long periods of weightlessness.

The highly successful orbiting and recovery of the Project Mercury Friendship Seven manned space capsule on February 20, 1962, with Col. John Glenn making three orbits in 4 hours and 56 minutes highlighted the manned space travel to date. There are some 18 manned space flight and support launches scheduled in 1962.

Table 2-11 MANNED SPACE FLIGHT AS OF MARCH 1962

Man	Gagarin	Shepard	Grissom	Titov	Glenn
Date	April 12,'61	May 5,'61	July 21 '61	Aug. 6,'61	Feb. 20,'62
Type of Flight	Earth orbit	Suborbital	Suborbital	Earth orbit	Earth orbit
Altitude (miles)	203	115.696	118	159	162
Distance (miles)	25,000	302	303	435,000	3 orbits
Flight Time	108 min.	15 min.	16 min.	25 hrs, 18 min.	4 hrs, 6 min.
Peak Velocity	17,400	5100	5280	17,750	17,100
Vehicle Name	Vostok 1	Freedom 7	Liberty Bell 7	Vostok II	Friendship 7
Spacecraft Weight	10,395	4031.7	4040	10,430	4050

b. Physiological Measurements

In most cases clinical methods of performing body function measurements are not satisfactory or entirely feasible for space-vehicle application. A survey conducted at Martin-Denver (Ref. 233) pointed out that some sort of equipment was available to measure nearly all physiological parameters but that many of these devices were not suitable for the requirements of prolonged space flight. They were rarely of low power, light weight, small, rugged, comfortable, non-restricting to subject and capable of accurate and reliable operation in abnormal environments of temperature, pressure and acceleration. Some of the more common physiological measurements are: blood pressure, skin temperature,

233 Gleason, G. W., "Bio-Instrumentation for Space Flight," Proceedings of National Telemetering Conference, 1960

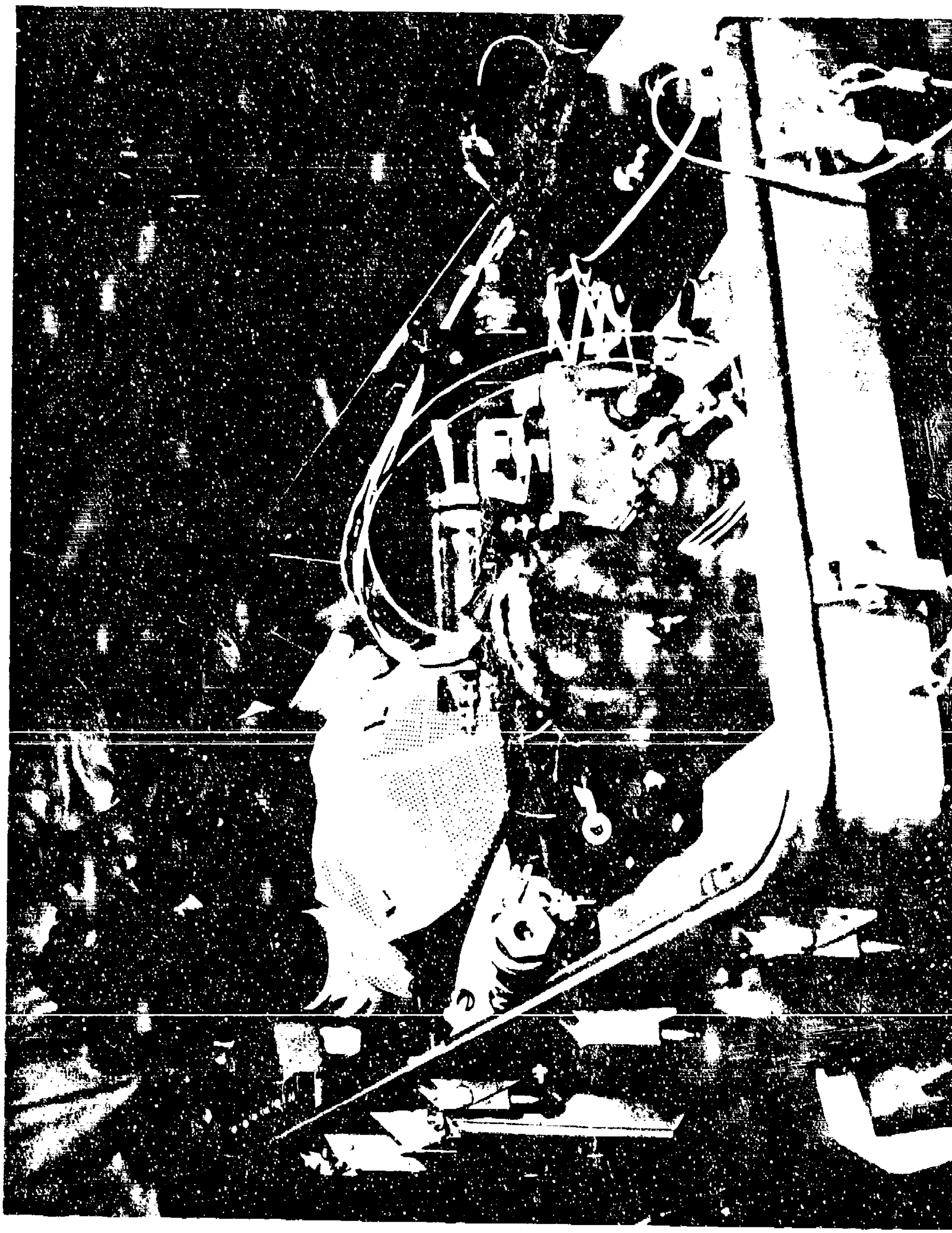

Fig. 2-135 Enos, a 5-1/2 year old chimpanzee, is fitted into his pressure couch prior to a three-orbital flight from Cape Canaveral, Fla. Weighing 37-1/2 pounds and measuring 38 inches in height, the male chimpanzee was selected from among a group of five animals which had been trained for the National Aeronautics and Space Administration's Project Mercury flights.

heart beat, electrocardiogram (EKG), electroencephalogram (EEG), galvanic skin resistance (GSR), and respiration.

An associated group of measurements applicable to manned spacecraft are termed "life support" measurements. They consist of measurements of: oxygen concentration, carbon dioxide concentration, other gases, gas pressure, gas flow, and liquid flow. Typical over-all instrumentation requirements for a manned orbital type space vehicle (Ref. 234) are given in table 3-6 (See Section III)

To understand the approaches to the application of transducing elements to physiological measurements, a brief description of some of the bio-signals are given. (Ref. 235) Needle electrodes in direct contact with single nerve fibers register about 20 microvolts. Skin electrodes over a large muscle give a wide range of less than 2 uv during practiced relaxation to 3000 uv in voluntary exertion. A range of 50 uv to 300 uv of signal are obtainable from surface scalp electrodes. Eyeball electrode potentials vary from 50 uv to 3000 uv depending on efficiency of placement. Electrodes placed just under the eyebrows or just under the eyes may have about 25 uv or more and can indicate eyelid response. EKG signals are relatively high from 500 uv to 2 mv. GSR changes on the palms of the hand and soles of the feet can be as high as 25% following sudden mental stress. See Figure 2-136 for representation of muscle fiber impulse. The commonly accepted frequency types in EEG are: alpha rhythm at 8-13 cps, normal for resting subjects with eyes closed; beta rhythm at 14-30 cps occurring during periods of mental effort; delta rhythm of 0.5 to 3.5 cps associated with extreme physical stress; and theta rhythm appearing during mental stress periods. See Figure 2-137 indicating electrical response from human brain. Normal pulse frequency is around 72 pps. A response of 0-50 cps is considered adequate heart-beat analyses. Rate of breathing is normal at about 16 inspirations per minute for resting individuals.

Blood pressure measurements consists of two discrete pressure measurements; "systolic," a higher pressure, and "diastolic."

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234 Ellis, A. B., "An Airborne Data Collection, Telemetering, and Ground Data Processing System for Development Flight Test of an Orbital Type Space Vehicle," Proceedings of National Telemetering Conference, 1960

235 Fo d, A., Foundations of Bioelectronics for Human Engineering, NEL Research Report 761, April 1957

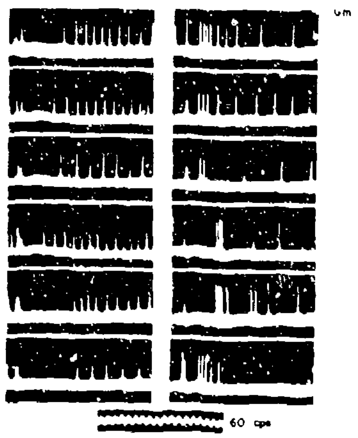

Figure 2-136

Electrical response of a single muscle fiber. Impulses are nearly constant in amplitude, and have a spike-like form without sinusoidal characteristics. This bioelectrical record was made by Drs. Eldred and Tokizane at the Veterans Administration Hospital, Long Beach, California.

Figure 2-137

Electrical responses from multiple muscle fibers. Left, stress during mental work. Right, relaxation level (about 4 microvolts). From the Lehigh University Bioelectric Laboratory.

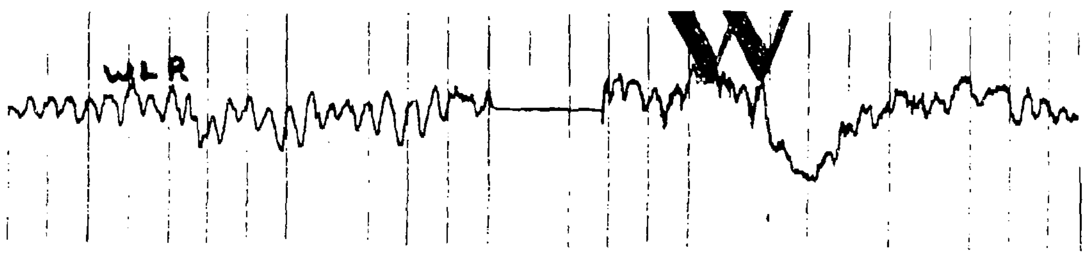

Figure 2-138

Electrical response from the human brain. Left, alpha rhythm during relaxation. Right, brain wave during arithmetical calculation. From the Lehigh University Bioelectric Laboratory.

Both must be known to diagnose properly. The best method is cannulation--pressure measurement by direct insertion into the artery. Practically, indirect methods such as arm cuffs, finger cuffs, ear cuffs, and artery indenting probes are used in manned space vehicle application. These methods are relatively awkward and a really good, all-purpose method is yet to be developed.

In a study by Webb Associates (Ref. 236) for NASA, the state-of-the-art for automated blood pressure measuring devices was investigated for evaluation in choosing such devices for application in the Mercury Program. Blood pressure devices made for measurement under conditions of activity exist at the Air Force School of Aerospace Medicine, the Ames Research Center, Edwards Air Force Base, Wright-Patterson Aeronautical Systems Division, at AiResearch and at the Systems Research Laboratories. All these devices make use of a microphone pickup to detect the escape of arterial occlusion as a blood pressure signal.

A brief description of each of these devices and its advantages and limitations may be found in Appendix IV.

Development studies are being carried out at the Stanford Research Institute and at MIT using a very sensitive capacitance pickup applied to the radial artery, which is capable of detecting mean arterial pressure with systolic peaks and diastolic lows. At the Air Force Flight Test Center at Edwards a method is being studied involving continuous measurement of pulse-wave velocity. The measured delay between each R pulse of the electrocardiogram and the arrival of the corresponding pulse wave at a chosen anatomical location is related to blood pressure, and may be most useful for following rapid transient changes in pressure.

Heartbeat or heartrate signals can be obtained from a cardiac microphone or may be extracted from the complex electrocardiogram waveform. The main disadvantage using a microphone pickup is its sensitivity to other mechanical vibration, movement of clothing against pickup, and in many cases, subject speech sounds. Proper signal conditioning (selective frequency response) and directional isolation and shielding to gain better signal in presence of high environmental noise is necessary in this application.

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236 A Survey and Evaluation of Methods of Measuring Blood Pressure for Immediate Space Flight Programs, Final Report on Contract NASr-51, Webb Associates, June 1961

In electrocardiogram (EKG) the 60 to 80 millivolt heart measurements to ample potentials are attenuated to 1 to 5 millivolts depending on the location of the electrodes on the body, necessitating the use of high gain amplifiers. Care must be exercised in employing adequate shielding to obtain usable signal to noise ratios. At Boeing (Ref. 237) in instrumentation for EKG is provided by a transistorized differential amplifier, miniaturized to 7. 6 cm by 4. 4 cm by 1. 9 cm weighing 94 grams. Gain levels are 1000 x and 2500 x. The frequency response is uniform up to 150 cps and the the phase and gain at low frequencies are controlled so that a step impulse of two seconds duration is reproduced faithfully.

In medical evaluation, this amplifier was found to give records identical to those produced with large type clinical electrocardiographs.

In field work, electrocardiographic data taken with the miniature instrument has been used in combination with heart sound data (also taken with the miniaturized equipment described in the next section) to study heart rates and phase relationships of heart excitation, contraction and blood ejection. An antero-posterior (front electrode on chest, rear electrode on back) electrode lead is usually used to reduce the amount of noise and base line shift which is caused by body motion and the consequent stretching of the skin where an unwanted piezoelectric-like effect occurs.

It is thought that analyses of the brain waves of an astronaut can yield important information about the state of consciousness, about hyperventilation and about abnormal neurological disturbances. Low blood sugar levels and high body alkalinity and acidity levels are thought to be ascertainable, as the existence of these abnormal chemical conditions produce characteristic brain wave patterns.

In electroencephalogram (EEG) measurements a high gain amplifier is again needed and their associated problems are a disadvantage in space craft use. The Boeing Space Medicine Section has medically validated a miniaturized electroencephalograph amplifier 10 cm by 7. 6 cm by 1. 9 cm weighing 168 grams. It has a gain of 100, 000 x, a low frequency time constant of 170 milliseconds and a frequency response up to 100 cps.

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237 Edmunds, A. B. Jr., Megel, H., Bark, R. S., "Space Physiology and Miniaturized Space Medical Instruments," <u>National Telemetering Conference</u>, 1960

Skin temperature measurements may be made using thermistor devices. These should be tested for high repeatability characteristics and their accuracy will depend greatly upon mounting arrangement and thermal insulation from external environment.

The average body temperature is usually thought of as the familiar value, 98.6°F. This value has been obtained by averaging thousands of oral temperature readings at different times for different individuals. A more reliable indicator of body temperature is the rectal temperature, which is usually one degree F Higher than the normal oral temperature. Temperatures vary throughout the body. Temperatures taken in any one place vary slightly during the twenty-four hour day and also vary from day to day. Small variations such as these, however, will only be of incidental significance for the space medical monitor. Marked elevations or depressions of rectal or peripheral temperatures will be of greater interest.

Temperature elevations of several degrees may be caused by bacterial or viral infection, emotional states, ingestion of toxic substances, dehydration, excessive cabin or space suit temperatures and high relative humidities. Depression of temperature may be produced by shock, bleeding and other related types of incidents.

Bead thermistor rectal probes have been designed and used but have time constants in the order of several seconds. Using a thermal insulated thermistor under the arm gave readings, which on the average paralleled rectal readings within 0.3°C.

Galvanic skin resistance (GSR) measurement changes can be interpreted to indicate mental stress or alertness, and sweat rates. A moisture-sensing element (Ref. 238) has been employed in measurement of thermal sweat.

Respiration measurements involve rate and volume determinations. Chest expansion devices are common and where properly fitted so slippage discomfort are not problems, offer simple measurement solution. One type employs a chest band with a spring

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238 Roy, O. Z., "An Electronic Device for the Measurement of Sweat Rates," IRE Medical Electronics. Vol. ME-7, No. 4, October, 1960

return potentiometer so mounted that expansion of elastic band moves rotary wiper arm of the potentiometer. Disadvantages are that a different calibration curve is obtained for each individual and for each of his general body positions. Strain gages are also used in chest expansion measurements. Gulton Industries Model MF-401 respiration transducer employs a cantilevered strain gage mounted in a face mask to be worn over mouth and nose, to sense breathing rate and depth.

At the Aerospace Medical Division at Wright-Patterson (Ref. 239) a small unit was designed to monitor both heart rate and respiration rate. Dry silver cloth electrodes were chosen for chest electrodes and placement selected for minimum interference from muscle action potentials. (Ref. 240). Three electrodes were used, one ground and two for EKG voltage pickup. Since only heart rate was being determined frequency limiting was employed in the amplifier decreasing further the response to other signals.

The respiration rate transducer consisted of a non-elastic chest band, with an electrolyte-filled rubber tube as the expansion link. See Figure 2-139. A 1/8 inch inside diameter, 3 inch long tube, filled with a copper sulphate solution (5-10%) was used. The tube was sealed with two pure copper electrodes at the ends. This resulted in a completely reversable electrolytic system for a limited operating time. (Electrolytic action on electrodes limits operating time-ac excitation would eliminate this factor).

The resistance range of this transducer depends on the dimensions and on the concentration of the electrolyte. A wide range of resistance can be made (about 300 to 20,000 ohm) for the given dimensions with varying electrolyte concentration.

To protect the rubber tube from being squeezed when used inside a pressure suit, a steel wire spring was wound around the tube. The transducer is fastened to a nonelastic belt, so that the

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239 Marko, A. R., Monitoring Unit for Heart and Respiration Rate, WADD Technical Report 60-619, August 1960

240 Tolles, W. E., Carbery, W. J., A system for Monitoring the Electrocardiogram During Body Movement, WADD Technical Report No. 58-453, April 1959

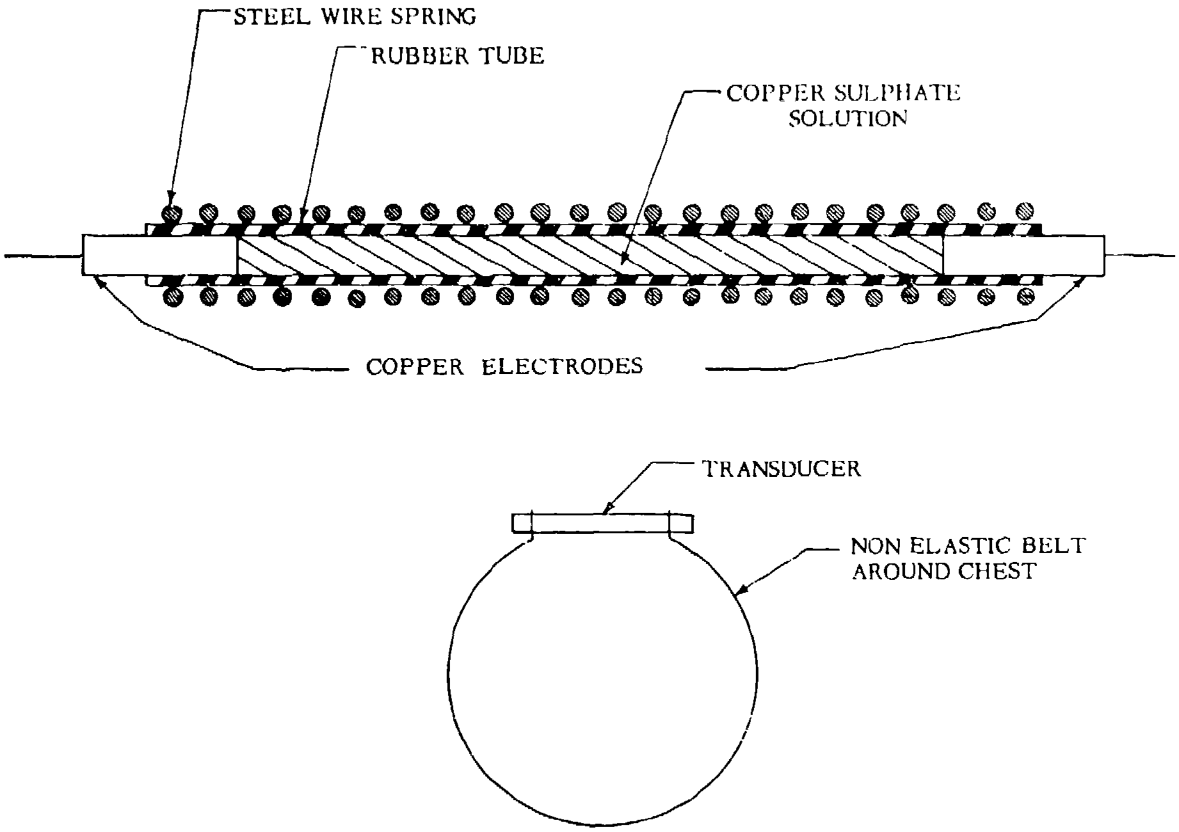
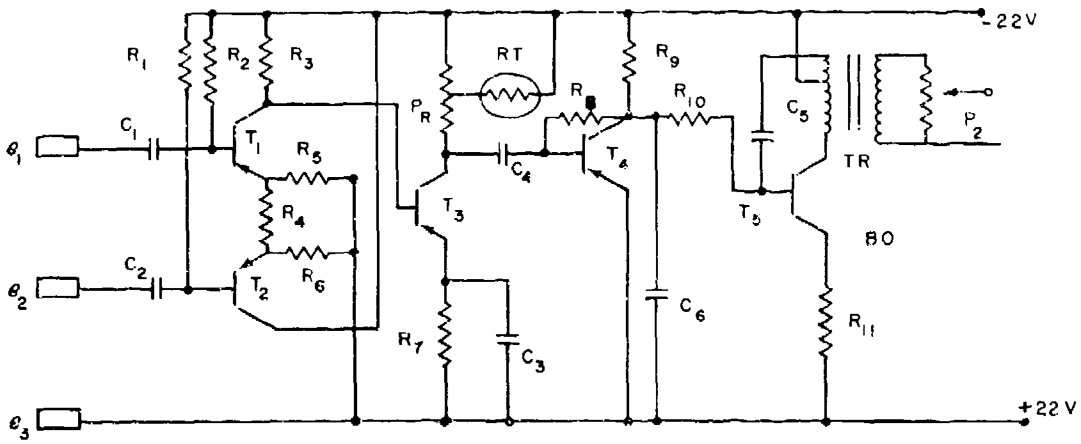


Fig. 2-139 Respiration-Rate Transducer

whole extension of the chest extends the tube. Normal breathing gives a resistance change of 5 to 20 percent, heavy breathing gives up to 150 percent.

The electronic system of the monitoring unit is shown in the circuit diagram in Figure 2-140. The first transistors (T_1, T_2) are of a differential amplifier stage, with a voltage gain of 10. Simple selection of transistors for equal current provides a common mode rejection of about 300:1. The base-to-base input impedance is 25,000 ohms. Capacitors on the input (C_1, C_2) limit the lowest frequency to about 1.5 cps for a 6-db drop. In the second stage, the resistor-capacitor combination (R_7, C_3) in the emitter reduces the lowest frequency to 8 cps for 6 db. This frequency limitation removes interference from body movements and electrode resistance changes to a high degree, but does not attenuate the QRS complex of the EKG significantly (main frequency about 20 cps).

A potentiometer (Pr) is located in the second-stage collector. It is paralleled by the electrolytic respiration transducer (R_t). The output from the respiration signal can be properly adjusted with the potentiometer. The third stage is a feed-back stabilized amplifier. In its collector circuit, a capacitor (C_6) limits the high frequency cutoff to 40 cps for a 6-db drop. This removes interference from muscle activity potentials. The amplifier voltage gain for the 3 stages is about 6,000 over a frequency band of 12 to 30 cps. This amplifier modulates the frequency of the blocking oscillator (BO), producing a tone with a frequency of about 800 cps. Modulation by the QRS part of the EKG occurs in the form of short blips creating high or low pulse tones, depending on the electrode polarity. Respiration causes slow shifts in the frequency corresponding to inhalation and exhalation. The secondary windings from the transformer (TR) employed in the blocking oscillator deliver a signal amplitude of 8 volts peak-to-peak. This signal can be used to modulate a standard transmitter for telemetering purposes (proper amplitude is adjusted with potentiometer (P_2), or may be connected with a telephone line or tape recorder). Monitoring heart rate and respiration rate is performed in the simplest way by listening, or if direct recording is required, by using a special discriminator circuit.



e_1, e_2, e_3 EKG ELECTRODES

C_1 C_2 TANTALUM CAPACITORS 9MF25V

C_3 TANTALUM CAPACITOR 25MF25V

C_4 TANTALUM CAPACITOR 50MF25V

C_6 TANTALUM CAPACITOR 1.75MF25V

C_5 CAPACITOR 0.002 MF 100V

T_1 to T_5 TRANSISTOR 2N43

TR TRANSFORMER UTC DOT 25

RT RESPIRATION TRANSDUCER

P_R 25 KΩ

P_2 25 KΩ

R_1 R_2 R_9	1.2MΩ	1/4 W
R_3	15KΩ	1/4 W
R_4	1.2KΩ	1/4 W
R_5 R_6	27KΩ	1/4 W
R_7	51KΩ	1/4 W
R_8	12KΩ	1/4 W
R_{10}	1MΩ	1/4 W
R_{11}	2.2KΩ	1/4 W

Fig. 2-140 Circuit Diagram of Monitoring Unit

c. Diagnosis and Display

Use of the telemetered data from physiological sensor in a space vehicle is primarily to monitor the physical condition of the man to insure his safety. It also has great documentation value for use in planning the succeeding missions. However, during the real time receipt of data it will be analysed to determine if the man's condition is normal or as planned, to sense any developing conditions that could lead to harmful or abnormal physiological functions. It is desirable that data be presented to monitoring console such that a meaningful indication is given on the astronauts physical condition. Voice communication and television, preferably color, are highly desired by monitoring physicians. More sophisticated displays and indicators are really needed such that the many physiological measurements may be monitored and related to each other in real time and compared to predetermined patterns of such data to determine normality of over-all body functions. By use of programmed measurements and computer diagnosis (relating and comparison with stored information) an output single indication could be given satisfying real time monitoring operator. Deviations from normal output would be used as error signals to indicate alarm, program various physiological measurements to be made and/or displayed in greater detail and where feasible to initiate corrective operational changes or procedures (shift body position, alter body cooling, exert aiding pressure to body areas, etc.)

To supply time correlated data for computer type diagnosis physiological sensors must be integrated with a number of the measured parameters of the space craft immediate and predicted operation. Thus as in many complex instrumentation problems, the ability to employ real time analysis of large amounts of related data, will return answers only available through indirect measurements.

At the Lafayette Clinic in Detroit, (Ref. 241) Dr. Albert Ax and George Zacharapoulos have designed a system for high-speed analysis of psychophysiological data (physiological reactions to psychological states). The design goal was a practical method of analyzing multi-channel recordings of variables such as heart rate

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241 "Medical Instrumentation Today," Readout, Volume 3, No. 4, Ampex Instrumentation Products Co.

skin temperature, palmar sweating, muscle potentials, and so on. These variables would be subjected to both statistical and functional analysis with respect to each other and to specific research questions.

The system is composed of four main sections: the physiological transducers, a 24 channel polygraph (for visual monitoring in real time and for editing), a data logger (for converting to digital and recording on magnetic tape) and a digital computer. The Visicorder polygraph is equipped with high-gain amplifiers and other modifying circuitry required to match the several transducers to the system. A cardiotachometer converts the period between heart beats into an analog voltage. Finger pulse pressure is picked up by a piezoelectric transducer, processed by a peak detector and hold circuit so as to present a continuous voltage for sampling by the data logger. Muscle potentials which indicate muscle tonus and contractions are integrated and recorded once per second. Bridge circuits measure skin temperatures and the palm skin conductance (as measures of skin blood flow and palmar sweating). Respiration is obtained from a strain gage displaced by changes in chest and abdomen circumference.

The transducer signals are also fed into the EPSCO data logger. A high-speed 29 channel electronic commutator samples each variable at least 10 times the maximum expected frequency of the variable. For example, respiration, which might reach a maximum rate of one-per-second, is sampled 10 times-per-second. The slowest sampling rate is one-per-second. An analog to digital (A to D) converter accepts each sample from the commutator and converts it to an 11-bit binary number. Format programming circuitry enables digital recording on tape in a format acceptable to the Bendix G15 computer for later analysis.

By enabling simultaneous consideration of data from these various systems of the body (behavioral, physiological and biochemical) it is hoped that more fundamental parameters may be found which are useful for describing the emotional and motivational systems that are disturbed in mental illness.

SECTION III

TRANSDUCER APPLICATIONS

3-1 INTRODUCTION

A sizable volume could be written about the use and application of transducers in rocket sleds, sled tracks, aircraft, missiles, satellites, and future spacecraft. In this section an attempt will be made to present a few examples of over-all instrumentation requirements encountered in tests and operational flight programs. The nature of the following information ranges from generalities to specifics. Many general applications are indicated, and operational characteristics pointed out in Section II under associated transducer measurement fundamentals. In this Section general information is repeated relating to basic usage of transducers, and where information is obtainable, unique applications of transducers and unique usage of measurement principles is reported. The aspects of selecting a transducer are briefly discussed. Evaluation remains to be an engineering test and analysis problem for each particular application. References will be noted where applicable indicating detailed studies of instrumentation to solve measurement problems.

3-2 GENERAL

a. Selection Criteria

The selection of a specific transducer for a particular application remains more of an art than a science because the choice between available alternatives nearly always represent a compromise between desirable and undesirable characteristics. Transducer discussions in Section II have included some of the characteristics which must be considered in the selection of each type; however, they have not been presented in a consolidated listing. Table 3-1 presents such a list, by broad categories, to assist the transducer user in the analysis of his requirements and selection of transducers which most nearly satisfy them.

Not all of the criteria set forth in Table 3-1, of course, are applicable in every instance of transducer selection. In fact, the assessment of the relative importance of the various criteria, and the extent to which each is

Table 3-1. Factors to Consider in Selecting Transducers

Factors Which Depend on the Characteristics of the Expected Input Variable:

Range (maximum and minimum values to be measured)
Overload Protection
Frequency Response
    Transient Response
    Resonant Frequency

Factors Affecting the Transducer Input/Output Relation:

Accuracy
Linearity
Sensitivity
Resolution
Repeatability
Friction
Hysteresis/Backlash
Threshold/Noise Level
Stability
    Zero Drift
    Loss of Calibration with Time

Factors Relating to the System of Which the Transducer is a Part:
Output Characteristics Size and Weight Power Requirements Accessories Needed Mounting Requirements Environment of Transducer Location Cross Talk Effect of Presence of Transducer on Measured Quantity Need for Corrections Dependent on Other Transducers
Factors Relating to Measurement Reliability:
Ease and Speed of Calibrating and Testing Time Available for Calibration Prior to and/or During Use Duration of Mission Stability Against Drift of Zero Point and Proportionality Constant (continued)

Table 3-1. Factors to Consider in Selecting Transducers (continuation)

Vulnerability to Sudden Failure (Probability of proper performance for a given life time) Fail Safety (Will transducer failure represent system failure, or invalidate data from other transducers?) Failure Recognition (Will transducer failure be immediately apparent so that subsequent erroneous data can be rejected?)
Factors Relating to Procurement:
Is Item Off-the-Shelf? Must development be done to make it operational? Price Availability and Delivery Previous Experience with the Vendor Availability of Calibration and Test Data from Manufacturer

satisfied by the available transducers, are points which must rest upon the judgment of the responsible engineer. Many of the items in this table are self-explanatory. For others, there are so many different definitions that a fair comparison of transducers requires careful attention to the way in which each term is defined by the manufacturer. Typical of this are such items as accuracy, resolution, and linearity. This problem area has resulted from the fact that standard definitions have not been established and adopted by both users and manufacturers. However, within the next year or so, it is expected that standard nomenclatures and definitions will be prepared and accepted through coordination between major users and manufacturers.

b. Mounting Considerations

A fundamental question which should be kept in mind when considering a transducer for a given application is "will the transducer output really correspond with the physical quantity which is to be measured?"

To some degree, the addition of a transducer will affect the behavior of the system itself. For example, inserting a flowmeter into a line will normally introduce additional fluid friction, which will result in an alteration to the flow rate. Similarly, the attachment of a vibration pickup to a thin plate may alter the natural frequency of the plate, and hence its response to certain vibrations. Finally, a temperature probe attached to a surface constitutes a local thermal inertia which may tend to smooth out the temperature variations which would otherwise be sustained. To be sure, with proper precautions, the alteration which the transducer imposes on the measurand can usually be made negligibly small, and this is often precisely the obligation on the system engineer.

In some cases, the "feedback" into the physical system from the transducer is not objectionable. Thus, if the flowmeter of the above example is to be present in every instance of the physical system (e.g., as part of a control loop) then its effect on the system is simply a system design parameter, and not a source of measurement error. On the other hand, where the transducer is inserted in only one model (as for test purposes), one must be careful in accepting the measured results as being representative of the performance of other models without transducers.

Even where feedback is of no concern, serious measurement errors can result from improper mounting of transducers. While it is impractical to attempt to set up mounting criteria for all types of transducers, the

following questions point out certain common pitfalls of transducer installation:

1. Acceleration and Vibration: Is the accelerometer or vibration transducer rigidly attached to the mass whose acceleration or vibration is to be measured?

2. Pressure: Is the pressure transducer at the end of a connecting cavity or tube whose added path length can cause transient errors, standing waves or a hydrostatic pressure difference? In pressure measurement of moving fluids, is the presence of dynamic pressure accounted for?

3. Flow Rate: Is the flowmeter protected against jamming by solid particles entrained in the fluid?

4. Temperature: Does heat flow through the transducer to or from the environment to the extent that a significant temperature differential exists between the transducer and the material whose temperature is to be measured? Are the junctions between thermocouple wires and attached leads always kept at equal temperatures? If the measured temperature is that of a moving fluid, are the stagnation effects accounted for? Does the transducer exchange radiation with walls which are at a different temperature from the fluid?

5. Voltage and Current: Do slip rings or other commutative devices introduce noise voltages which are significant with respect to the signal? Are coils in resistance thermometers, galvanometers, magnetometers, etc. adequately shielded from extraneous magnetic fields emanating from other equipment?

Prior to implementing a measuring system the engineer must ask himself numerous questions like those listed above so as to minimize the chances of wasted time and funds which could be directly attributed to a lack of engineering forethought.

c. Environmental Effects

A knowledge of the transducer's output characteristics while exposed to a laboratory-type environment cannot be used to completely predict its suitability for the intended application. From previous telemetry records, or extrapolations, or theoretical analysis, the engineer must list the types and ranges of environments to which the transducer will be exposed. Further, he must take into account their durations and the magnitude versus time profile. In many instances, he can only estimate these parameters, and may later find such estimates to be off by 100% or more; nevertheless, it is essential that he begin with an estimate which is based on something more than pure intuition.

After establishing a set of environmental conditions, it becomes necessary for the engineer to make decisions, based on his experience and an awareness of results from other test programs, regarding the subjection of transducers to simulated environments in the laboratory. If it is a question of evaluating the transducer from the standpoint of drift, hysteresis, noise, etc., or testing it to destruction, he has a choice of whether or not to carry out such tests. However, if he is striving for accuracy in measurement during a missile flight, for example, he has little choice but to run the transducer through the simulated environment so as to prepare a calibration curve. Once he has assured himself that transducers of a certain type, batch, or manufacture, are consistently identical in environmental effects, he may elect to run calibrations only on random samples. Such procedures are, however, generally applicable after the missile program goes into a production phase. They are not suited to research and development programs.

The selection and simulation of environments is a major engineering function within all organizations which are designing aircraft, missiles, space vehicles, and rocket sleds. In particular, the simulation of combined environments is taking on greater and greater importance as more is learned from telemetry recordings and laboratory investigations. Some facilities can provide combined temperature and vibration tests, and other combinations will shortly be available (See Section V).

The transducer engineer must have an inquisitive mind. He must explore for the "not obvious" and investigate what he considers to be possible areas of difficulty in the final application. For example, the dynamic response of an oil-damped accelerometer may be as advertised by the manufacturer providing that it is vibration tested with the sinusoidal force exerted in a direction

parallel to both the earth's gravity vector and the sensitive axis of the accelerometer. However, the dynamic response may change radically if the accelerometer is turned on its side so that the gravity vector is perpendicular to the direction of the moving mass within the accelerometer (sensitive axis). In the latter case, the accelerometer is vibrated horizontally so that the sinusoidal force is still applied along the sensitive axis. Another case is that of pressure transducers which are exposed to high-level acoustical noise. Where such noise is expected, and sensitive pressure measurements must be accomplished, the engineer may discover that he is highly limited in his choice of transducers or he may elect to investigate the performance of certain other transducers when exposed to noise. Another consideration with which the telemetry engineer is being confronted more often is that of the radiation resistance characteristics of transducers. With the discovery of the Van Allen belts and forthcoming nuclear propulsion systems, the engineer must familiarize himself with radiation terminology, effects on materials, testing techniques, and test facilities.

d. Operating Time

Depending on the type and purpose of the vehicle, the "mission time" may range from a few seconds to years. In the case of those with very long mission time, this will constitute the greatest percentage of total operating time required of the transducer. For short mission time vehicles, such as ballistic missiles and rocket sleds, the required total operating time with satisfactory performance will be much greater than the mission time.

In the case of sleds, some of the transducers are not considered to be expendable and must be used for numerous repeated tests. Further, operating time will be consumed by calibrations and normal pre-run checkout procedures.

The actual flight of a ballistic missile may be preceded by literally hours of operational time requiring stable and reliable transducer performance. Upon delivery by the manufacturer, the transducer may undergo incoming electrical tests by "incoming inspection" personnel. Following this, it may receive electrical and environmental tests prior to installation in the missile. Missile checkouts at the factory require overall telemetry testing on more than one occasion. Following an initial factory checkout, the missile may be shunted aside to await repairs or installation of other components. Prior to its shipment, it would be given a final checkout. Upon arrival at the missile test range, the vehicle generally receives another series of tests while in a

horizontal position in the contractor's hangar. Erection at the launcher is followed by one or more tests against console checkout equipment and the ground-based telemetry system. Firing "holds" may necessitate additional checkouts before the launch actually takes place.

The engineer must take into consideration the duration of operating time which the transducer will be subjected to. At the beginning, he may realize that the transducer which he must utilize has a life-time which is short of the requirements. In this case, he may have no choice but to procure test, and calibrate extra transducers which are shipped with the missile as replacement components.

3-3 AIRCRAFT APPLICATIONS

a. General

Operational aircraft utilize numerous transducers which enable the pilot and flight engineer to adjust controls, evaluate safety conditions, and determine distance-to-go capability. Many of these transducers are not considered herein since they are not intended for telemetry purposes. Others, although not used on the aircraft as telemetry transducers, are useful as transducers for telemetering purposes (e. g., air speed, rpm). Still other transducers are used in conjunction with airborne computers for computing Mach number and distance-to-go.

Transducers are employed quite profusely in drone aircraft and test programs for the development of new aircraft types. For example, engine measurements may run as high as sixty during a given flight.

The following paragraphs present only a small portion of information which could be written concerning the applications of transducers in aircraft.

b. Examples of Applications

Tables 3-2 and 3-3 present some measurements, measurement ranges, accuracies, operational time, and outputs of transducers used on drone aircraft and test programs for jet fighter aircraft. Since this information was received from single sources, it cannot be said to be typical and, in fact, it is questionable that a set of typical conditions may be set forth. Although the types of measurements may be common to many programs, the ranges,

Table 3-2. Transducer Applications in Drone Aircraft

Measurement	Transducer Type	Range	Accuracy	Operational Time	Output
Equip. compt. temp.	Resistance thermometer	0-250°F	±5°F	5 hrs	res/temp
Tail pipe temp.	Chromel-alumel thermocouple	0-1300°F	±25°F	25 hrs	mv/temp
Oil intank temp.	Res. thermometer	0-500°F	±5°F	10 hrs	res/temp
Fuel temp.	Res. thermometer	±20° to +200°F	±5°F	10 hrs	res/temp
Outside air temp.	Thermocouple	-65° to +120°F	±2°F	25 hrs	mv/temp
Rudder position	Potentiometer	±20° (0-5000 ohms)	±0.5°	25 hrs	0-5 v dc
Longitudinal acceleration	Accelerometer	±2.5 g	±0.1 g	25 hrs	0-5 v dc
Vertical acceleration	Accelerometer	±10 g	±0.2 g	25 hrs	0-5 v dc
Lateral acceleration	Accelerometer	±1 g	±0.1 g	25 hrs	0-5 v dc

(continued)

Table 3-2. Transducer Applications in Drone Aircraft (continuation)

Measurement	Transducer Type	Range	Accuracy	Operational Time	Output
Fuel remaining	Fuel flow	100-1000 lbs/hr	0.5%	25 hrs	freq/flow
Fuel remaining	Fuel flow	1000-25,000 lbs/hr	0.5%	25 hrs	freq/flow
Vibration in equip. compt. (3-axis, hard mount)	Vibration	15 g; 3-750 cps	±5%	5 hrs	8 mv/g
Oil tank pressure	Pressure	0-5 psig	±0.05 psig	5 hrs	0-5 v dc
Oil pressure aft of pump	Pressure	0-50 psig	±0.5 psig	5 hrs	0-5 v dc
Compressor discharge pressure	Pressure	0-100 psia	±0.5 psia	10 hrs	0-5 v dc
Inlet total pressure	Pressure probe	0-1 psid	±0.1 psid	10 hrs	0-5 v dc
Tail pipe pressure	Pressure			20 hrs	
Altitude in equip. compt.				25 hrs	
Airspeed	Pressure			25 hrs	

Table 3-3. Transducer Applications in Jet Fighter Aircraft Test Programs

Measurement	Transducer Type	Range	Accuracy	Operational Time	Output
C. G. vertical acceleration	Accelerometer (variable reluctance)	±10 g	Linearity, 5% over full range	1 hr	Active half of modulating bridge
Altitude	Absolute press. (variable reluctance)	0-30 psia	Linearity, 5% over full range	1 hr	Active half of modulating bridge
Indicated air speed	Differential press. (variable reluctance)	±20 psid	Linearity 5% over full range	1 hr	Active half of modulating bridge
Pitch, roll, and yaw rates	Individual rate gyros (slidewire pickoff)	Pitch, ±50°/sec; roll, ±300°/sec; yaw, ±15°/sec	Linearity, ±1.5% over full range; resolution, 0.4%	1 hr	Slidewire center tap to one end is proportional to rate. Acts as active half of modulating bridge
Control surfaces position (aileron, stabilizer, rudder, and yaw damper vane)	Precision potentiometer	May be geared so that surface movement of ±20° results in potentiometer swing of ±160°	Linearity, ±0.5% over full range; resolution, 0.155%	1 hr	Active half of modulating bridge

(continued)

Table 3-3. Transducer Applications in Jet Fighter Aircraft Test Programs (continuation)

Measurement	Transducer Type	Range	Accuracy	Operational Time	Output
Tail bending and torsion	Bonded strain gage	500 ohms	Linearity approx. 1% (depends on mounting)	1 hr	Varies from 1 to 25 mv/v, depending on surface rigidity. Four gages uses to form modulating bridge. two or three bridges may be used in parallel.
Exhaust gas temperature	Chromel-alumel thermocouple	Up to 850°C	Linearity, approx. ±2% over full range. Thermocouple is referred to 0°C by means of ice bath.	1 hr	3 mv (full range) drives sub-carrier oscillator.
Engine rpm	Tach generator	Gear ratio of 0.5619: 1.0 gives 4192 rpm at engine max. of 7460 rpm	Linearity, approx. ±1% 0-100% rpm	1 hr	26-40 v at 0-70 cps (corresponds to 0-100% rpm)

(continued)

Table 3-3. Transducer Applications in Jet Fighter Aircraft Test Programs (continuation)

Measurement	Transducer Type	Range	Accuracy	Operational Time	Output
Yaw and pitch angle	Yaw and pitch angle boom vane	Yaw angle, ±10°; angle of attack, +90° to -45°		1 hr	Vanes drive potentiometer through gear train

accuracies, and operational times will differ because of differences in mission requirements which are reflected in aircraft operational capabilities, such as maneuverability, fuel consumption, air speed, etc.

c. Temperature Measurements (Ref. 242)

(1) Ambient Air Temperature

The ambient air temperature T, which is one of the main parameters in performance flight testing, is the temperature which would be measured by a thermometer which is at rest relative to the ambient air. If, as is the case for a thermometer attached to an aircraft, the thermometer is moving through the air, the measured temperature T_m will be higher than this ambient air temperature.

The magnitude of this temperature rise can easily be calculated if the thermometer is placed in a stagnation point on the aircraft. At these points, the air is brought to rest by a very nearly adiabatic process and the resulting temperature T_s (stagnation temperature) may be calculated by use of the following equation:

$$T_s = T + \frac{V^2}{2c_p g} = T\left(1 + \frac{\gamma - 1}{2} M^2\right) \qquad (3\text{-}1)$$

where

T = ambient air temperature

V = true air speed

c_p = specific heat of air at constant pressure

g = acceleration of gravity

γ = ratio of specific heats at constant pressure and at constant volume

M = Mach number

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242 Pool, A., "Temperature Sensing Techniques," AGARD Flight Test Manual, Vol. IV, Part IIA4, pp. IIa4:4 - IIA4:8.

At all other points of the surface, the temperature rise will be lower, because of no adiabatic processes in the boundary layer. Since both stagnation points and boundary layer will be present on the thermometer body, the temperature T_m measured by the thermometer will have some intermediate value between T_s and T. This is expressed by

$$T_m = T + \epsilon (T_s - T) = T + \epsilon \frac{V^2}{2c_p g} = T \left(1 + \epsilon \frac{\gamma - 1}{2} M^2 \right) \qquad (3\text{-}2)$$

The coefficient ϵ is called the recovery factor of the thermometer. It has been shown both theoretically and experimentally that for a flat plate placed at zero incidence in an airstream, the recovery factor is independent of Mach number, pressure, etc. It is only affected by the stage of the boundary layer and has a value of 0.85 if the boundary layer is laminar and of 0.91 if it is fully turbulent. If other shapes of the thermometer body are used, or if the plate is at some incidence to the airflow, the recovery factor will change with Mach number and pressure. These effects are generally small for low subsonic Mach numbers.

When the recovery factor is known, it is possible to calculate the air temperature just in front of the thermometer from the measured temperature T_m and the Mach number or true airspeed just in front of the thermometer. This recovery factor can be determined by wind tunnel tests.

In connection with flight testing, the term recovery factor is defined in a slightly different way. It is the factor which makes it possible to calculate the ambient air temperature if the measured temperature and the true airspeed or Mach number of the aircraft are known. These two recovery factors may differ appreciably if the local true air speed V_t at the point where the thermometer is placed is not equal to the true airspeed of the aircraft V. The change of state from V to V_t occurs by an adiabatic process, the measured temperature T_m is derived from the local state of the air by a nonadiabatic process.

It can be shown that the "flight test" recovery factor ϵ' is related to the recovery factor ϵ determined in the wind tunnel by

$$\epsilon' = 1 - (1 - \epsilon) \frac{V_t^2}{V^2} \qquad (3\text{-}3)$$

If ϵ is appreciably less than unity and if V_t differs from V, the difference between ϵ and ϵ' is considerable. In such cases, it is essential to determine ϵ in actual flight.

In flight testing aircraft which do not fly faster than about M = 0.5, the normal thermometer placed in the airstream is generally used because of its simplicity. The recovery factor is determined by flight tests. No accurate knowledge of this factor is necessary at these low speeds. For an aircraft flying at 200 kts, the temperature rise will be approximately 5°C. If the ambient air temperature must be known with an accuracy of ±1°C, the accuracy required in the recovery factor is ±20%.

The sensing elements used are nearly always resistance thermometers shaped as a flat plate or a tube. To insure rapid response, the resistance wire is usually in direct contact with the air. It is however, surrounded at some distance by a shield which prevent heat radiation effects.

At higher airspeeds, the accuracy with which the recovery factor can be determined becomes too low for the accurate calculation of the temperature correction, which rises to more than 40°C at M=1. At those speeds, stagnation temperature probes are used, in which the sensing element is mounted inside a stagnation chamber which is open in the direction of flight, so that it is fully surrounded by air which is very nearly at stagnation temperature. Recovery factors of better than 0.99 can be attained by careful design. Special care must be taken that the heat losses from the stagnation chamber by conduction and radiation are very small.

Resistance thermometers are often used in stagnation temperature probes, but they have the disadvantage that they dissipate a relatively large amount of heat into the small stagnation chamber. This must be taken away by a larger amount of flow through the chamber. Therefore, thermocouples are sometimes preferred because they produce much less heat. A great advantage of the stagnation thermometer is that the difference between "wind tunnel" and "flight test" recovery factors becomes negligible (See equation 3-3 for $\epsilon \rightarrow 1$), so that the recovery factor can be determined once and for all by any one of the available methods. It should be noted here that equation (3-2) applies in subsonic and supersonic flows, even if the probe is placed behind shock waves produced by the aircraft.

Large errors may result from using the two above-mentioned types in air supersaturated with water vapor (so that water may condense on the sensing element) and under icing conditions. Normal flight tests

will hardly ever be executed under these circumstances, but they will prevail, e. g., during tests to study ice accumulation on aircraft. In these cases, a reverse-flow thermometer may be used. This is essentially a reversed stagnation temperature probe which is open to the wake behind the instrument and in which a small flow is induced in a direction contrary to that of the main flow around the aircraft. The probe has a low recovery factor (about 0.65) which is not very constant, but it has been found to function well even under extreme icing conditions.

For all previously mentioned types, the ambient air temperature has to be calculated from the measured temperature, the Mach number and the recovery factor. The vortex thermometer, however, can be adjusted to indicate the ambient air temperature directly. In this device, the so-called Ranque-Hilsch effect is used, which states that the temperature in the core of a vortex decreases with increasing speed of rotation of the vortex.

The probe consists of a tube placed perpendicularly to the flight direction, in which a vortex is generated by introducing stagnation pressure through a tangentially placed intake. By changing the surface of the intake hole, the speed of rotation can be adjusted so that the axially placed sensing element indicates ambient air temperature.

(2) Temperature Measurements in Engines

Temperature measurements in reciprocating engines are hardly of importance in flight testing. Cylinder head thermometers of the thermocouple type (usually copper-constantan) are used to check engine cooling, but are not essential in the assessment of aircraft performance and stability. Ambient air temperature, the measurement of which is discussed in the previous paragraphs, is the only temperature which influences engine performance.

In turbine engines, the temperature of the combustion gases in the jet pipe is of primary importance both for the engine control and for the determination of the engine performance. The measuring problems encountered here are similar to those of ambient air temperature measurement in that the thermometer is exposed to a high-velocity gas stream; however, there are some complications, as follows:

(1) The temperatures encountered are very much higher (of the order of 1000°C in

normal jetpipes and up to 2000°C in afterburners).

(2) Radiation, which increases with the fourth power of the absolute temperature, reduces the attainable accuracy.

Because of these facts, thermocouples usually of the chromel-alumel type, are universally used for these measurements. Thermocouples used for the control of the engines are often simply placed in the gas stream, and engine performance is given as a function of the indicated temperatures. For the accurate assessment of engine performance in flight, however, the true temperature of the gas stream must be measured so that recovery factors, radiation losses, and time constants of the instruments used must be accurately known. A large amount of research is being expended on the determination of recovery factors and time constant of suitable probes. Radiation shielding is achieved by using multiple metal or ceramic shields.

(3) Measurement of Surface Temperature

An important part of the flight testing of modern aircraft is expended on temperature measurements all over the aircraft. The strength of the main structure may be endangered by conduction or radiation of heat from the engines or the armament, by the impingement of engine jets on the fuselage or tail skin, and by aerodynamic heating of the aircraft skin at very high Mach numbers. Moreover, the large electric currents in electric and electronic accessories may also produce so much heat that their service life is dangerously shortened. In most of these cases, surface temperatures must be measured to determine that the limits of safety are not being surpassed.

Sensing elements for these purposes must meet the following demands;

(1) They must be in very good thermal contact with the parts whose temperatures are to be measured.

(2) They must be effectively shielded from radiation and from airflows which are the cause of the high temperatures.

(3) They must neither weaken the structure to any appreciable amount nor disturb the airflow around it.

The construction of the sensing elements largely depends on the shape of the structure and on the environmental conditions. Both resistance thermometers and thermocouples are extensively used. Thermocouples have the advantage that they may be brought into direct metallic contact with the structure if suitable precautions are taken in the measuring circuit. Shielding can easily be provided by pieces of asbestos cloth or similar materials glued to the sensing element.

A very convenient method which may produce very good results is the use of paint or crayon streaks which change color or substance when heated above a certain temperature. Maximum temperatures can be indicated in this way at intervals of about 5°C, in the range of about 50 - 150°C, and at greater intervals up to about 800°C.

(4) Thermostats

Many instruments require a constant temperature if accurate results are desired. Examples are piezoelectric transducers (barium-titanate), the sensitivity of which changes appreciably with temperature, and instruments using oil as a damping medium, the viscosity of which varies with temperature. These instruments may be enclosed by an insulating case in which a constant temperature somewhat above the highest ambient temperature is maintained by an electric heating coil controlled by a thermostat.

The most generally used type of thermostat is a device consisting of a bimetal strip which closes a heater circuit when a temperature falls below the preselected value, and breaks the circuit when this temperature is exceeded. For aircraft applications, bimetals with snap action are often used, in which contact is made or broken by a quick and relatively large displacement of the moving contact surface. In this way, contact chatter due to vibrations at near-contact temperatures is prevented, so that contact wear and radio interference are much reduced. A disadvantage of this type is that there is a small difference between the temperatures at which contact is made and broken so that temperature constancy generally is less than in the normal type.

3-4 MISSILE APPLICATIONS

a. General

Missile measurements by way of transducers and telemetry systems may be divided into the general classes shown in Figure 3-1. Each of these classes involves a large number of individual types of measurements.

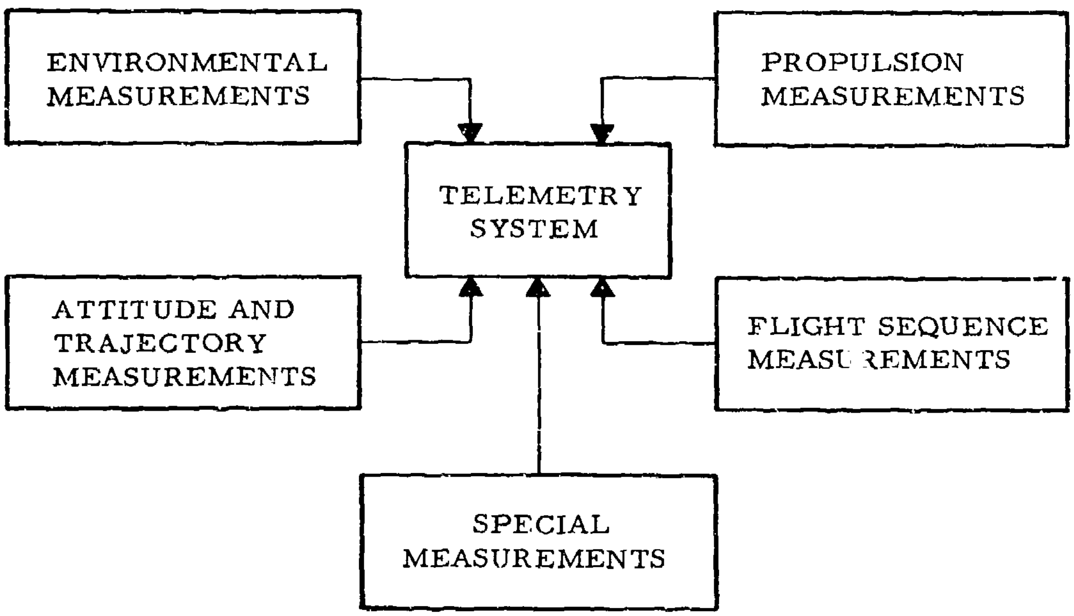

Fig. 3-1. Missile Measurements

For example, propulsion measurements include fuel level, fuel quantity, flow rate, fuel temperature, tank pressures, fuel pump pressure, motor chamber pressure, thrust, coolant temperature, turbine rpm, flame shield temperature, currents through solenoid valves, and many others. Furthermore, each measurement type may involve two or more ranges which must be instrumented by individual transducers. By way of example, Table 3-4, and Figures 3-3 and 3-4 are presented to show some transducer applications in aerodynamic and ballistic missiles.

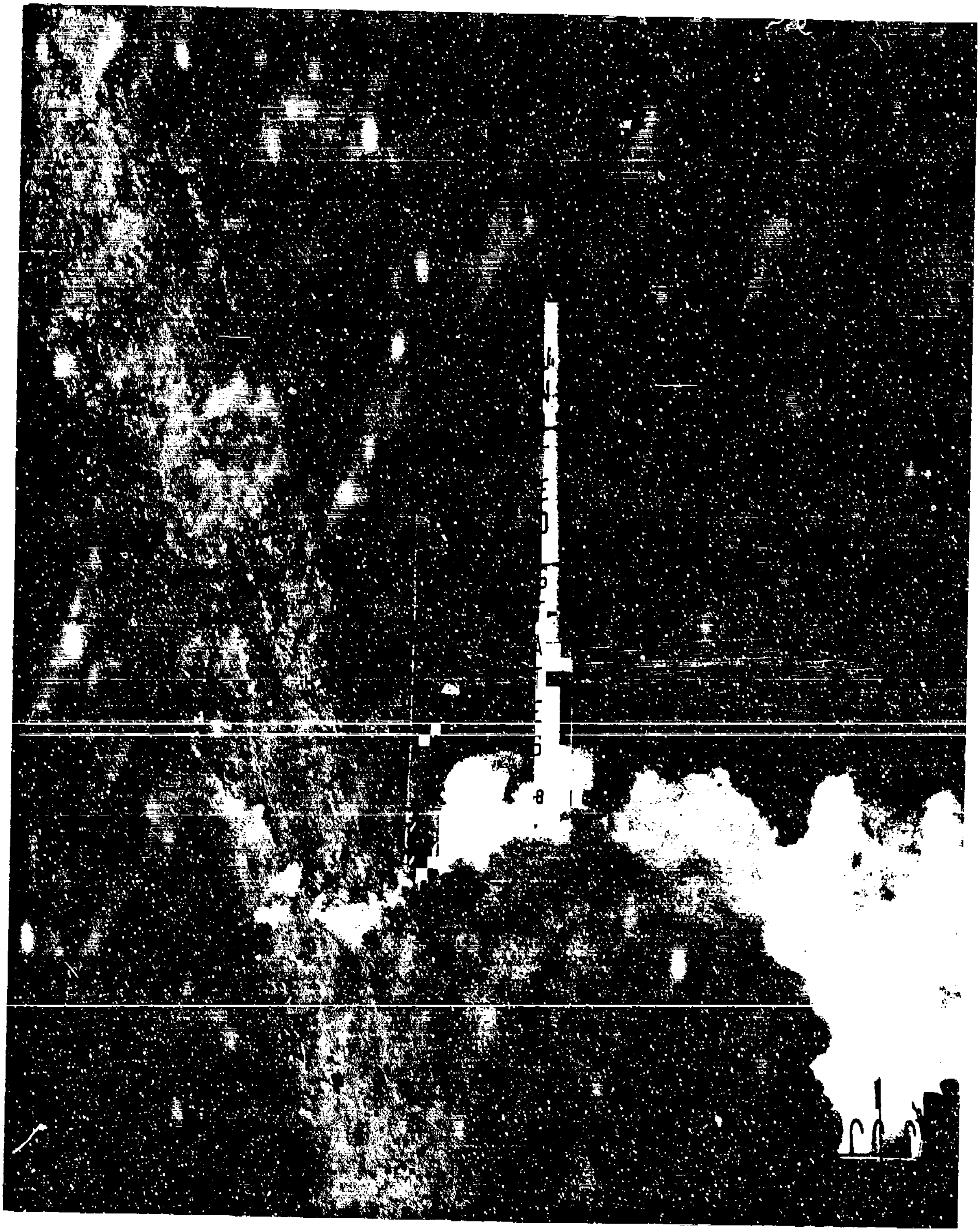

Fig. 3-2 Launch of Mercury Scout Missile from Cape Canaveral.

As explained in the introduction to this section, it has not been possible to compile, write and edit a thorough text on transducer applications. The following material is limited in scope in that it applies primarily to some of the work which has been carried out by the Army Ballistic Missile Agency.

b. Environmental Measurements (Ref. 243)

(1) Temperature

Four principal temperature measurement areas normally required are: (1) surface or skin (2) temperatures resulting from rocket engine exhaust (3) propellant, and (4) ambient air at various critical points within the missile. Four types of gages may be used for temperature measurements: resistance thermometers, thermistors, thermocouples, and thermopiles.

(a) Resistance Thermometers

Early in the history of telemetry, resistance thermometers of platinum wire with ceramic backing were used where low-range surface measurements were required. The adapters used to convert outputs to values suitable for telemetry were very crude. There was no amplification, and only deflection-type Wheatstone bridge circuits were used. Where temperature ranges were high, special types of resistance thermometers were required. These were usually very fragile and difficult to work with, and many temperature ranges could not be covered adequately.

While the resistance thermometer was helpful in obtaining certain measurements, its use was limited to temperatures below 800°C. Its fragility was a definite problem; however, resistance thermometers are still widely used to measure aerodynamic heating effects. For measuring skin temperatures, they are generally made of nickel wire a little larger than 0.001 inches in diameter. Some are backed with silicone rubber and are simply clamped to the missile skin. The upper limit of measurement for this particular device is about 500°C because of the temperature limits of the insulating material.

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243 "Measurement and Telemetry Systems for Missiles," Army Ballistic Missile Agency, Vitro Engineering Co., Report No. 2331-2-59, pp. 8-17.

Table 3-4. Transducer Applications in an Aerodynamic Missile Test Program

Measurement	Transducer Type	Range	Accuracy	Output
Longitudinal acceleration	Linear accelerometer with undamped nat. freq. of 5 cps	± 0.5 g	Combined friction, resolution, and hysteresis, 0.04 g	0-3 v dc to subcarrier oscillator
Lateral acceleration	Linear accelerometer with undamped nat. freq. of 6 cps	± 1 g	Combined friction, resolution, and hysteresis, 0.1 g	0-3 v dc to subcarrier oscillator
Normal acceleration	Linear accelerometer with undamped nat. freq. of 10 cps max.	+3 to -6 g	Combined friction, resolution, and hysteresis, 0.1 g	0-3 v dc to subcarrier oscillator
Fin flutter (vibration)	Unbonded strain gage accelerometer	10 g; 20-2000 cps	Non-linearity and hysteresis combined, ±1% of full scale	12 mv full scale, open circuit, for 3 v excitation
Vibration at numerous points throughout the vehicle	Piezoelectric vibration transducers	0.1 to 400 g	±10% of stated calibration	5 mv/g

(continued)

Table 3-4. Transducer Applications in an Aerodynamic Missile Test Program (continuation)

Measurement	Transducer Type	Range	Accuracy	Output
Acoustic noise at numerous places throughout the vehicle	Piezoelectric microphone	127 to 155 db, 37 to 12,000 cps	±10% of stated calibration	100 mv/psi open circuit sensitivity. AC output to cathode follower, to ac amplifier, to subcarrier oscillator.
Jet engine fuel flow rate	Turbine flowmeter	2 to 20 gpm	±0.5% of full scale flow rate	0-3 v dc proportional to flow rate and ac voltage with freq. proportional to flow rate
Indicated air speed	Differential pressure transducer	150 to 850 knots		0-3 v dc
Engine inlet control position	Rectilinear potentiometer	Mechanical travel = 12.750 inches	Linearity, ± 0.75% of full scale	0-3 v dc
Engine fuel pump inlet pressure	Potentiometer type pressure transducers (three)	0-20 psia; 0-30 psia; 0-40 psia; 0-50 psia	Linearity, ±1% of full scale	0-3 v dc

(continued)

Table 3-4. Transducer Applications in an Aerodynamic Missile Test Program (continuation)

Measurement	Transducer Type	Range	Accuracy	Output
Engine fuel pump inlet pressure	Potentiometer type pressure transducer with Bourdon tube	0-100 psig	Linearity, ± of full scale	0-3 v dc
Engine fuel pump inlet pressure	Potentiometer type pressure transducer	0-250 psia	Linearity, ±1% of full scale	0-3 v dc
Elevator flutter (torsion and bending)	Strain gage, 4-arm bridge	10 to 150 cps	Limited by associated equipment	millivolts
Engine RPM	Tachometer	0-11, 500 RPM	Limited by readout equip.	Freq. and amplitude proportional to RPM
Equipment compartment temperature	Semi-conductor resistance element with 30 sec. time constant	-65° to +300°F	±1% of full scale	0-3 v dc from bridge
Hydraulic fluid temperature	Semi-conductor resistance element with 3 sec. time constant	+150° to +300°F	±1% of full scale	0-3 v dc from bridge
Air temperature	Wire wound resistance element	+100° to +350°F	±1% of full scale	0-3 v dc from bridge

(continued)

Table 3-4. Transducer Applications in an Aerodynamic Missile Test Program (continuation)

Measurement	Transducer Type	Range	Accuracy	Output
Fuel Temperature	Semi-conductor resistance element with 3 sec. time constant	-50° to +250°F	±1% of full scale	0-3 v dc from bridge
Instrumentation rack temperature	Surface temp. transducer with semi-conductor resistance element. Time constant = 3 sec.	-50° to +250°F	±1% of full scale	0-3 v dc from bridge
Free stream air stagnation temp.	Probe with chromel-alumel thermocouple. Time constant = 1.5 seconds		Recovery factor of 98%	Millivolts dc to chopper-amplifier to subcarrier oscillator

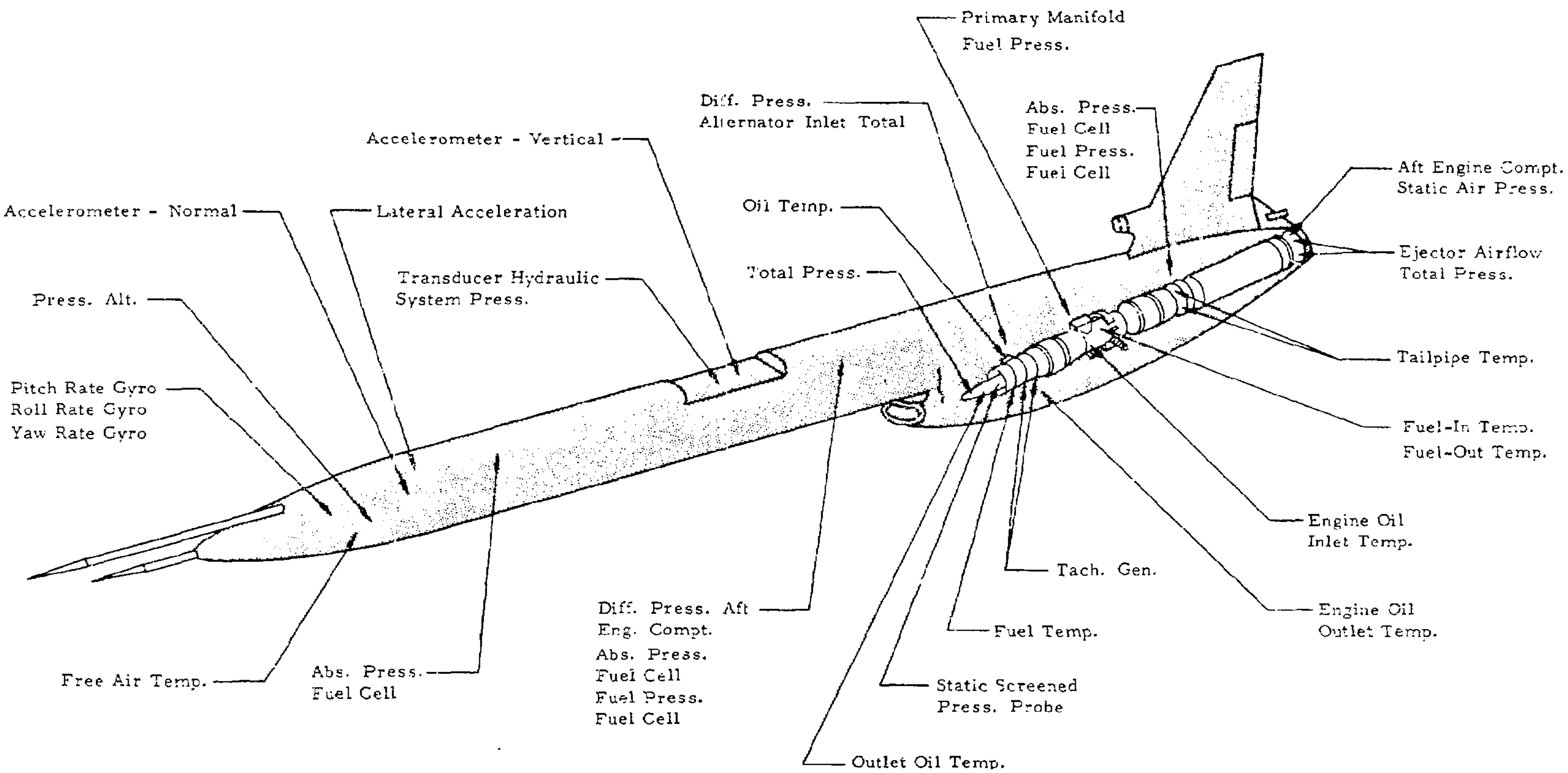

Fig. 3-3 A Typical Air Breathing Vehicle Showing Representative Applications of Transducers

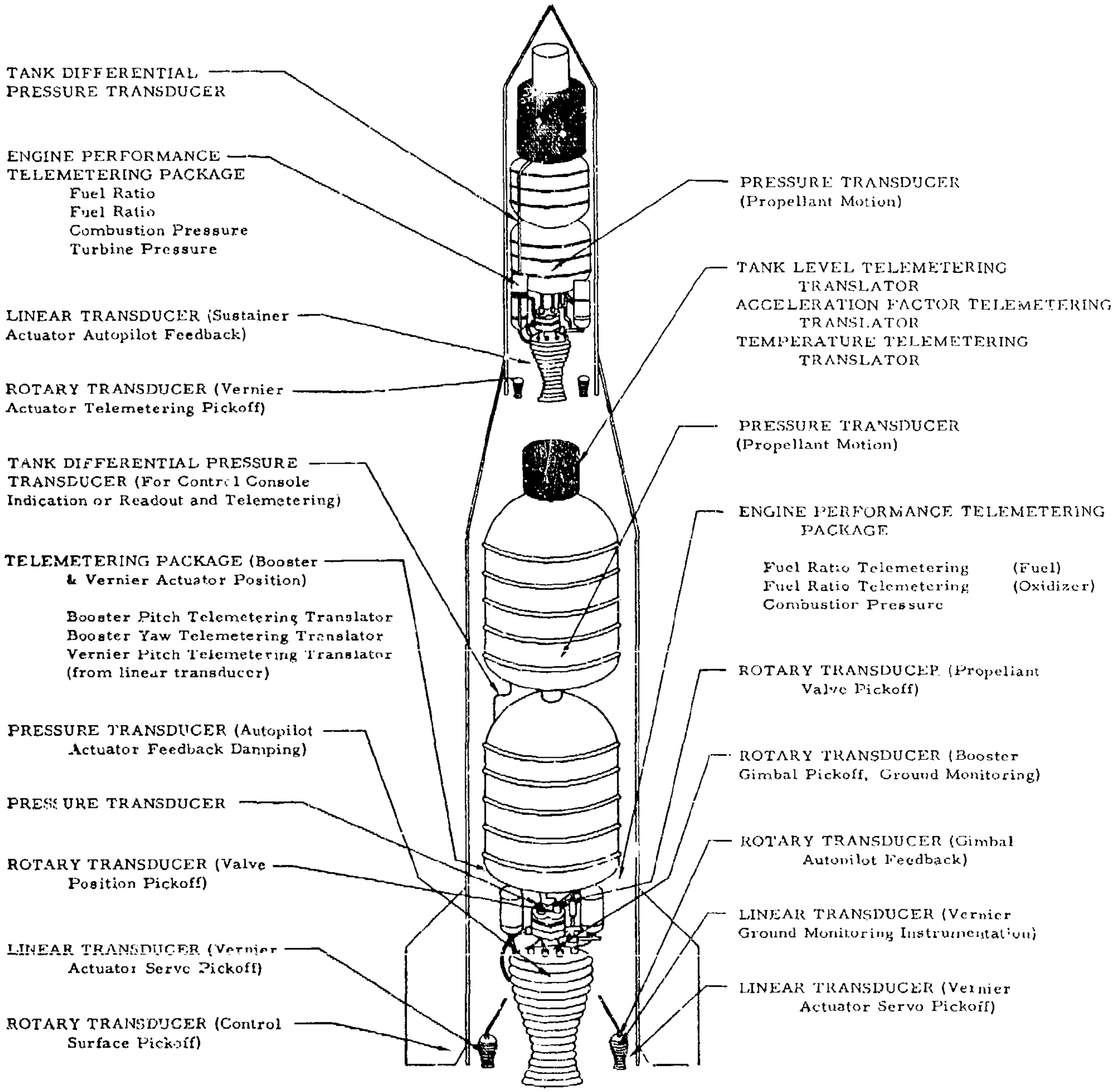

Fig. 3-4. A Typical Missile Configuration Showing Representative Applications of Transducers

(b) Thermocouples

The low output voltage from a thermocouple requires amplification before it can be used as an input signal to the airborne telemetry system. Amplification may be accomplished through use of dc amplifiers or chopper-amplifiers. These intermediate circuits are often called "signal conditioners." However, it should be noted that this terminology applies to all types of circuits which are used to convert transducer output signals to a form (e. g., voltage level, ac to dc conversion, etc.) which is compatible with the input requirements of the telemetry system.

Thermocouples are normally used where the temperature change will produce an output large enough, after being amplified, to cover the 0-5 volt dc range of the telemetry system input. Normally this means temperature spans greater than 300°. An example would be temperatures measured on missile skins subjected to aerodynamic heating. Thermocouples used for this purpose are welded directly to the skin.

The use of thermocouples for missile temperature measurement involves the choice of a location for the reference or cold junction, which must preferably be at a low fixed temperature, to increase the over-all range of the device. This is done very easily in the laboratory by placing the reference junction in an ice bath. This is obviously impractical for missile applications. To solve this problem, ABMA developed the "zone box" which is a device for providing an artificial reference junction temperature for each thermocouple and eliminates the use of long thermocouple leads.

(c) Thermopiles

In some cases, the output of a thermocouple, even after amplification does not have an output in the 0-5 volt range necessary for compatibility with the telemetry system. With a thermopile composed of two thermocouples, it is possible to get twice the output of a single thermocouple. Thermopiles, however, cannot be used if the thermocouple junctions are joined to the missile skin. In such an instance, a resistance thermometer is often preferred.

(d) Thermistors

Thermistors are thermally sensitive resistors that exhibit a resistance change of about 4% per degree Centigrade at room temperature.

The high temperature coefficient of thermistors, about ten times that of typical metals, makes these devices useful for temperature measurement. The temperature coefficient of a thermistor is negative; that is, the resistance of a thermistor decreases as temperature increases.

Thermistors are particularly useful to cover narrow ranges of measurements at extreme temperatures, such as those of LOX, which normally vary from minus 185 to minus 170°C. At these temperatures, thermocouples and resistance thermometers do not have sufficient output after amplification for the 0-5 volt measuring range. Fuel and air conditioning temperature measurements also require the use of thermistors.

(2) Vibration

Transducers which are commonly used in missiles for the measurement of vibration are the unbonded strain-gage type, the piezoelectric type, and the velocity (magnetic) type.

(a) Unbonded Strain-Gage Vibration Transducer

One type of strain gage transducer is shown in Figure 3-5 wherein four equal length strain-sensitive wire filaments are attached between a stationary frame and a movable mass. The filaments are connected to form a Wheatstone Bridge circuit as shown in Figure 3-6.

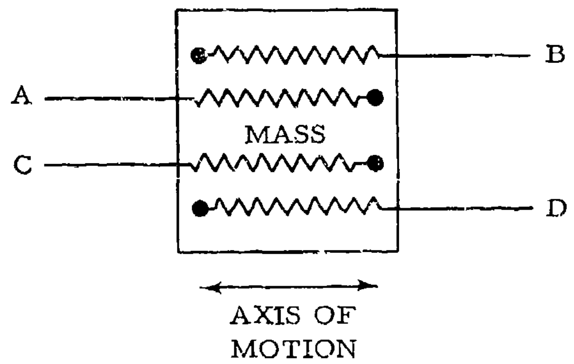

Fig. 3-5 Strain Gage Vibration Transducer

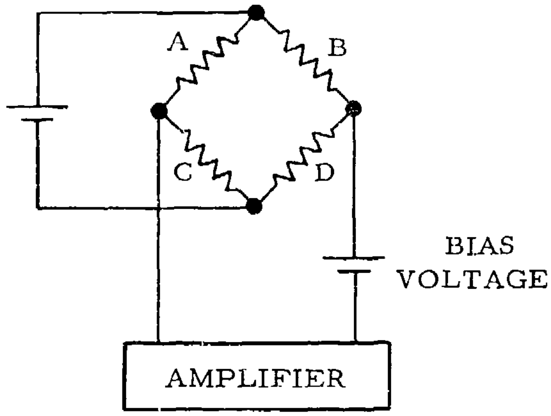

Fig. 3-6. Strain Gage Circuit

This transducer is used to sense low-frequency vibrations within the range of 0-300 cps. When the mass is at rest, the bias voltage causes a 2.5-volt output of the amplifier. The bias is necessary to prevent the transducer's output from going negative, because the direction of vibration is both plus and minus.

(b) Piezoelectric Transducers

This self-generating transducer type is used to measure vibrations in the approximate range of 10 cps to 2 kcs. They have a high output impedance and a cathode follower is necessary for impedance matching purposes. The application of piezoelectric material in cantilever beam construction had been used to develop an extremely light weight low cost vibration transducer (Ref. 244). Barium titanate crystals were employed and final design yielded a device of approximately 0.35 gram using adhesive cement type mounting, and having sensitivities in the 4 mv/g range. Linearity was within a 10% variation and indications of easily obtaining 2% or less variations. Repeatable frequency response of ±1.5 db were obtained. Lead zirconium was also tried for high temperature applications.

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244. Smith, Thomas D. and Spence, Harry R., "Designing a Lightweight Vibration Transducer." Parts 1 and 2, Electronic Industries, January and February, 1961.

(c) Velocity Vibration Transducer

This transducer type is used to measure vibration frequencies between 10 cps and 2 kcps. As compared with the accelerometer type devices which are dependent ofn the magnitude of the displacement, the velocity type sensor is dependent of the frequency. A wire wound core is placed between two permanent magnets. As its case is vibrated, the core and wire move back and forth, cutting permanent magnetic lines of force set up by the magnets and inducing a voltage in the coil wire. The output voltage is then calibrated against the vibration frequency. This device does not require a separate power source since the voltage induced in the wire is caused by the magnetic field of the permanent magnets.

c. Propulsion Measurements (Ref. 245)

Some of the transducers which are used in propulsion measurements are flowmeters, flowmeter converters, pressure transducers, pressure switches, continuous and discrete liquid level transducers, and accelerometers. The operating principles of several of these transducers are given in Section II of this volume.

A thrust measuring system for aircraft engines has been designed by Schaevitz Engineering (Ref. 246, 247) from the measurement of engine exhaust nozzle pressure ratio. The system is intended for installation in aircraft and gives a continuous indication of gross thrust, both on ground and in flight. It consists of three major components: a servo-driven indicator, an analog computer and a pressure probe set. The computer receives exhaust nozzle inlet pressure, and ambient pressure from an altimeter line or other source. From these inputs it computes gross thrust, producing an electrical signal output to drive and position the indicator. A pressure rake is installed in the engine to obtain nozzle inlet total pressure averaged across the exhaust gas flow path. Theory of operation and computational analysis on the Thrustmeter System is presented in detail in the Appendix IV-3 Thrust Fundamentals.

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245 Same as Ref. 243, pp. 23-29

246 System,Thrustmeter, Aircraft Engine, WADC Technical Report No. 53-302, November 1953

247 A Flight Thrustmeter for Turbo-Jet Engines, Schaevitz Engineering TR-100, November 1961

(1) Flowmeter Converter

In the turbine type flowmeter, the output signal is usually in the form of electrical pulses or a sinusoidal voltage whose frequency is proportional to the flow rate. For normal flow rates, the frequency may be 300 cps or greater. Because of the large amount of data which must be carried on high frequency channels, it is sometimes desirable to use a lower frequency channel for flowmeter signals. In such cases, an electronic count-down circuit may be used to lower the frequency to the desired value.

(2) Pressure Transducers

Many pressure transducers used in connection with propulsion measurements are Bourdon-tube type pressure transducers. They are used to measure pressures ranging from 100 to 3500 psig. Pressure measurements below 100 psi are often made with a capsule type transducer. A lever attached to the movable end of the tube or capsule actuates a wiper sweeping over a standard 5-volt wire-wound potentiometer, thus giving a dc output corresponding to the pressure. Since this measurement does not require a high frequency response, it is the most direct method of obtaining the pressure information.

(3) Pressure Switches

In many cases, a spiral type Bourdon tube is used in pressure switches to obtain a large actuating force per unit pressure. The spiral normally has 4, 6, or 8 turns, depending on the actuating force necessary. When the pressure attains a predetermined value, the Bourdon tube opens or closes a relay which in turn energizes some other device such as a pressure regulator. Only the opening or closing of the relay is telemetered; and as this is an on-off type measurement, it is normally superimposed on another measurement.

(4) Liquid Level Transducers

One of the ABMA methods of continuous level measurement uses a transducer consisting of a long cylindrical capacitor open at both ends and standing on end in the liquid, which serves as the dielectric. The gage forms one leg of a balanced bridge. As the liquid level falls, the total dielectric value changes and the bridge becomes unbalanced. The unbalance signal is amplified and transmitted to a servo motor which drives the balance potentiometer and continuously re-balances the bridge. The output is in the 0-5 volts range for telemetering.

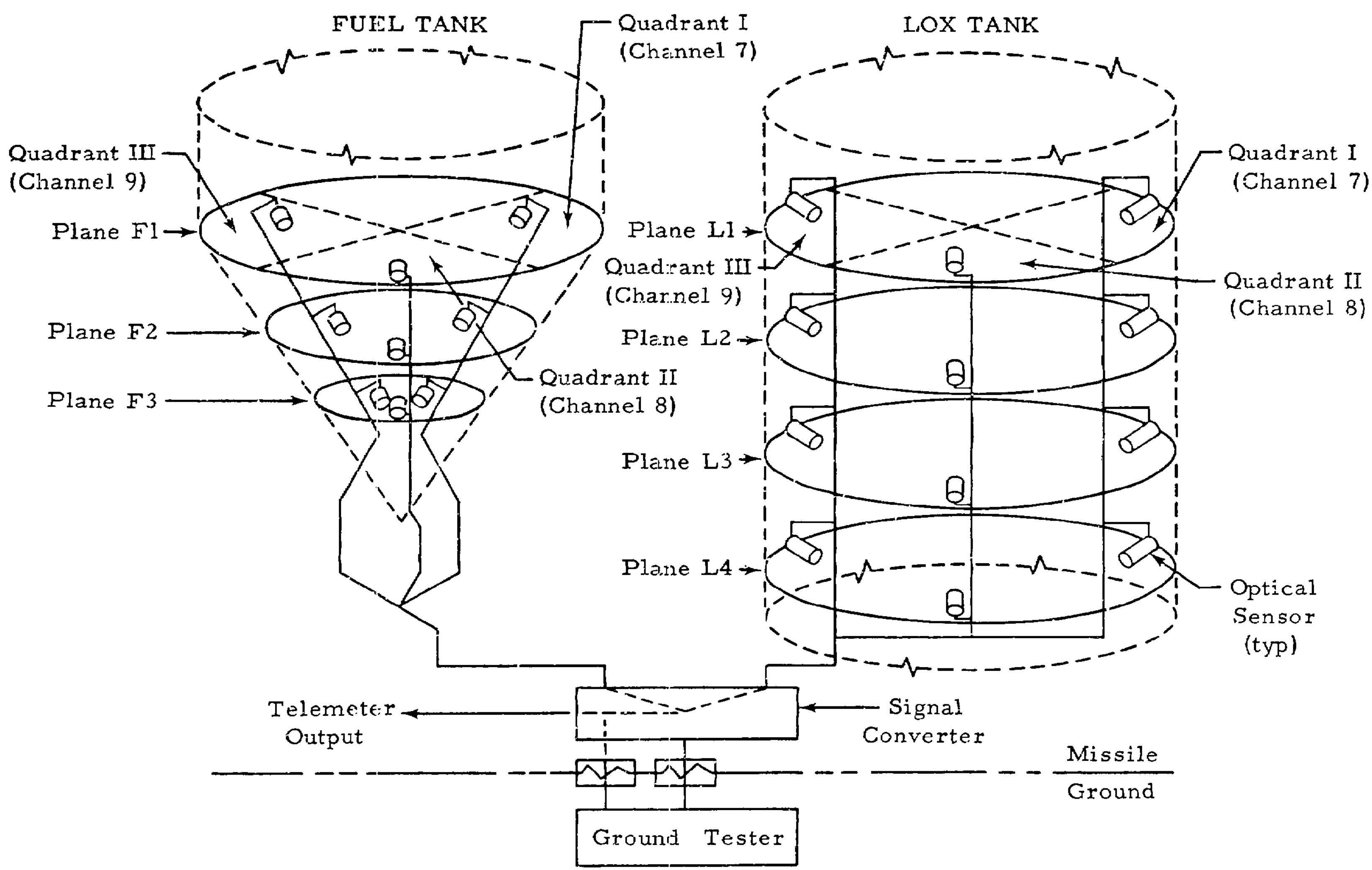

Fig. 3-7 Optical Liquid Level Monitor System

Figure 3-7 depicts a discrete point liquid level measuring installation using an optical system similar to that described on pages 175 -- 177 of this volume (Ref. 248).

As previously discussed in Section II under Thrust Measurements, many propulsion relationships involve acceleration measurements. A performance report (Ref. 249) evaluated a typical linear, seismic type accelerometer. The instrument tested was the Donner Model 4310. This device is comprised of a seismic system, position-error detector, restoring mechanism, and servo-error signal amplifier.

This type device is small, moderately accurate, low power consumption and readily available. Tests indicated adequate operation for many missile and space applications to measure acceleration, velocity (integrate output over a period of time for trajectory calculations, sensing pre-set acceleration levels to generate a shut-off signal for control as well as indication of performance of rocket engines.

Of interest to aerospace instrumentation is the application of the photoresistive technique to produce a high output accelerometer. (Ref. 250) Data Sensors, Inc. has designed such a device with a microminiature light source, a cantilever pendulum acting as a shutter and two photo transistors. Fig. 3-8 illustrates the operating principle.

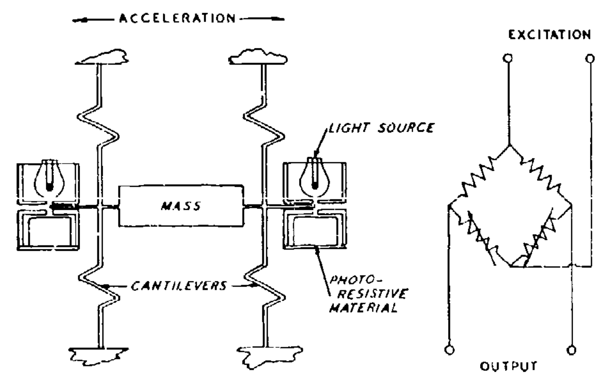

Figure 3-8 Accelerometer-Data Sensors, Inc.

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248 Same as Reference 168, pp., 8-18

249 Judge, H. R., Performance of Donner Linear Accelerometer Model 4310, Space Technology Laboratories, Inc., STL/TN 60-0000-09117, June 1960

250 "The Photo Transducer-A General Description", Data Sensors, Inc. Technical Bulletin

An excitation of 10 volts will produce a ±2.5 volt or 0-5 volt signal for operation directly into telemetry systems. Excitation voltages as high as 100 volts may be used to obtain higher output signals. Units have been packaged in as little as 1.3 cubic inches, weighing approximately 2 ounces. Extremely small movement of cantilever pendulum acting as a shutter to modulate light results in reported high natural frequency characteristic and very low (0.25%) hysteresis figure.

d. Angle of Attack Measurements (Ref. 251)

Attitude is measured by angle of attack transducers. Three types are the free air stream type, local drag vane type, and the local probe type.

(1) Free Air Stream Type

The free air stream type transducer is mounted on a boom at the top of the missile. This device has four vanes which keep the probe aligned in the air stream. Because this device is located in the free air stream it is unaffected by turbulence which exists around the body of the missile during flight. The vanes are attached to a universal mounted ogive. When the vanes are displaced by wind forces, two wipers move across two potentiometers causing the outputs to vary accordingly. Pitch and yaw may be accurately determined by using this device. In some cases, a static probe is used at the front of the free air stream type meter to determine the static air pressure. Data for one such transducer is included in Volume II of this Handbook.

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251 Same as Reference 243.

(2) Local Drag Vane Type

This type of angle of attack transducer has a vane at the end of an arm which is mounted so as to be in the airstream around the nose of a missile (See Volume II of this Handbook). A potentiometer or synchro may be mechanically linked to the arm to give a signal which is proportional to the angular displacement of the arm.

(3) Local Probe Type

Local probe angle of attack transducers are normally flown in groups of four: two for yaw and two for pitch. They consist of a probe having two slots placed 80° apart. Differential pressures between each of these slots is a result of the angle of attack. Pressure is directed into these slots, and fed into an inner chamber divided into two parts by a butterfly valve. If the pressure increases in one slot and decreases in the other, a differential pressure exists on each side of the butterfly valve. This valve moves until the pressure on both sides are equal and the 80° slots on the probe are again lined up in the air stream. The motion of the butterfly valve and probe is converted into an electrical signal through a potentiometer wiper connected to the shaft of the valve.

3-5 TRANSDUCERS FOR RE-ENTRY BODIES (Ref. 252)

The transducers discussed in the following paragraphs have been recommended in the above listed reference for use in re-entry bodies and other high-speed vehicles wherein high temperatures are encountered. Some of the devices are still in the development stage while others have been proven satisfactory in high-speed flight.

a. <u>Temperature Measurement</u>

For high-speed vehicles, the Tungsten-Ir[illegible] thermocouple is suitable for the measurement of stagnation temperature and a thin metal resistance thermometer may be employed for surface temperature measurements other than stagnation.

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252 Wacholder, B. V. and E. Fayer, <u>Study of Instrumentation and Techniques for Monitoring Vehicle and Equipment Environments at High Altitudes</u>, Radio Corporation of America, WADC TN 59-307, Vol. III, pp. 33-45.

(1) Tungsten-Iridium Thermocouple

Tungsten-Iridium thermocouples are capable of satisfactory performance in the temperature range of 3000° to 4000°F. They have good repeatability characteristics and an accuracy on the order of ±5%. The only significant drawback is their relative instability in the presence of oxygen. With proper insulation and protection, these thermocouples can be designed to function for lengthy periods. Temperature response of 2000° in a few seconds have been obtained with the bare thermocouple. Insulation from oxidative atmosphere will reduce the response time somewhat.

Protection of the thermocouple from oxidation and corrosion may be accomplished in several ways. The usual methods include gas tight metallic or ceramic wells or tubes. An ideal method would be to make the thermocouple an integral part of the surface material and located just below the surface in order to minimize response time. Another method would be to locate the thermocouple in a groove and cover it with a thin sheet of surface material. Available ceramic bonding cements are good to 2000°F. Another method of attachment makes use of a small disk of the skin material as one half of the thermocouple junction. The disk is electrically insulated from the vehicle by a ceramic insulator.

(2) Thin Film Resistance Thermometer

Thin film resistance thermometers are well suited for monitoring temperatures at critical structural regions because of their rapid response (on the order of microseconds), size (in the order of 1/10 micron thick), and sensitivity (temperature fluctuations of less than 1°F). They are about 75 times more sensitive than thermocouples and their sensitivity can be varied by varying the energizing current in the film. Further, they are easier to install than the thermocouple and do not require a reference junction or reference temperature measurement.

Resistance thermometers constructed of platinum paint on a glass insulator have given satisfactory performance in the temperature range of 200° to 300°F (Ref. 253). The main problem in the use of thin film resistance thermometers is that of providing a suitable bond between the insulator and the surface to be measured.

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253 Vidal, Robert J., "A Resistance Thermometer for Transient Surface Measurements," Cornell Aeronautical Laboratory, Inc., presented at the ARS Meeting, September 24-26, 1956, Buffalo, New York.

b. Pressure Measurement

(1) Dynamic Pressure Loading (Ref. 254)

The impact pressure transducer offers an attractive means for monitoring surface pressures on a hyper-velocity re-entry vehicle. The diaphragm of this transducer is an integral part of the vehicle's surface and it is capable of sensing impact pressures to several hundred psi.

In the application and fabrication of this transducer, a surface hole is located at the point where the pressure is to be measured. A tailored plug is inserted in the hole and plated simultaneously with the rest of the surface, except for a thin annular ring around the outside edge of the plug's end. In this manner, a rigid-center fixed-edge diaphragm is produced and a mechanically stiff combination results in small surface deflections with corresponding deformations distributed over the entire plug area. Deflections are on the order of microinches. A piezoelectroci crystal may be attached to the diaphragm for sensing the deflection; however, this has the undesirable requirement for a high shunt resistance which necessitates the use of an electrometer tube which is subject to the effects of shock and vibration.

(2) Internal-Pressure Transducer

The detection of small leak rates on the order of 0.005 psi/sec (0.254 mm Hg/sec) may be a realistic requirement in some re-entry and space vehicles. The Haven's Cyclic Pressure Gage (Ref. 255) is attractive for this purpose because it is rugged, has a small volume, and covers the range from atmospheric pressure down to less than 10^{-5} mm Hg.

The gage works on the principle that an ac signal can be obtained from a dc pressure transducer by cyclically changing the pressure at a given frequency. The ac signal amplitude is primarily a function of pressure alone. The gage contains two bellows which are each open to the pressure to be measured through a small hole (approximately 0.5 mm diameter). They are physically driven in a push-pull manner by an eccentric shaft attached to a small electric motor. Resistance wires within the bellows are used as

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254 Wrathall, Taft, "Measuring Impact Pressures of Re-entering Missile Nose Cones," ISA Journal, Vol. 5, No. 11, November 1958.

255 A Study of Flight Instrumentation for Vehicles Operating in the Fringe of, or Outside of the Earth's Atmosphere, Vol. IV, "Investigation of Sensing Techniques," Bell Aircraft Report No. 6009-001, WADC TN 59-567, Vol. IV, Part III.

sensing elements. Because the air flow to and from the bellows is restricted by the small holes, the pumping action of the bellows causes the gas to give up heat under compression and to take in heat when it expands. These temperature variations of the gas cause corresponding changes in resistance of the sensing elements within the bellows to create an ac signal. The temperature change of the gas (and resistance elements) is a function of the mass of the gas and hence of the pressure.

c. Vibration Measurement

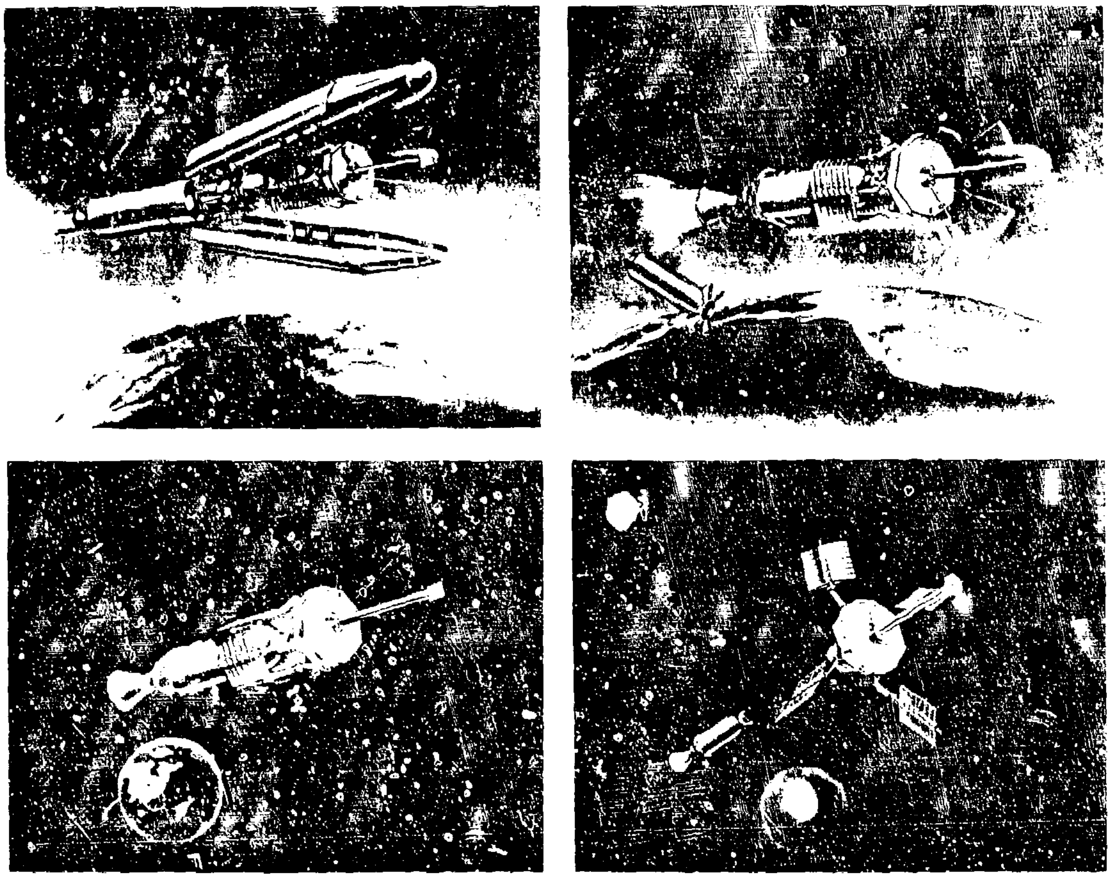
Vibration caused by boundary layer and power plant noise can be best monitored by piezoelectric vibration transducers. Frequencies up to 4000 cps demand an instrument which has a natural frequency of at least 10 kc. Transducers are available with sensitivities up to 50 mv/g. Frequency response from one cps to 15 kc is typical of commercially available units. By use of high-temperature materials, the piezoelectric transducer is capable of operating continuously at temperatures up to about 500°F. The temperature range may be extended by use of cooling methods, such as water jackets.

d. Acoustic Noise Measurement

The condenser microphone is well suited for the measurement of acoustic noise in high-speed vehicles where very high temperatures are encountered. Condenser microphones work on the principle of conversion of mechanical to electrical energy via an electrostatic field. One such transducer is constructed of stainless steel and glass compounds. The diaphragm is a clamped glass plate whose thickness varies from 0.004 to 0.013 inch, depending on the required sensitivity.

Temperature limitations of condenser microphones are imposed by the physical properties of cable insulation. Long-time exposure may be limited to approximately 300°F. For use at high temperatures, a probe tube may be threaded onto the end of the microphone to provide a point source pickup. By using a heat shield between the source and the microphone it has been possible to operate at temperatures as high as 1400°F. Higher temperature operation may be possible through use of a water jacket surrounding the probe tube.

Due to the high impedance of condenser microphones, it is necessary to use an impedance transformer device, such as a cathode follower. Other associated equipment includes an amplifier and a power supply.



NASA PHOTO NO.
61-S3-1 (Delta 6)

Fig.3-9 S-3 (Delta 6) Satellite

Upper left: The Delta is more than 40 miles high and 90 miles downrange when the second stage fires. Forty seconds later explosive bolts tear away the fairings which enclose the S-3 satellite.

Upper right: After coasting to about 1300 miles downrange and reaching an altitude of 160 miles, explosive bolts and retro rockets separate the second stage, and the third stage is spun up and fired.

Lower left: Yo-yo weights despin the third stage and S-3 satellite, and exhaust gases dissipate, during a 24-minute coast after third stage burnout, which occurs almost 2000 miles from Cape Canaveral when the engine and S-3 are traveling at a velocity of more than 24,000 miles per hour.

Lower right: The four solar paddles are released when an explosive-actuated cutter severs a nylon lanyard after the coast period. The Delta's third stage is separated from the S-3 by explosive bolts and a spring mechanism.

3-6 SATELLITES AND SPACEPROBES

a. General

The following material pertaining to instrumentation and data telemetering from space vehicles is presented as examples of present and future requirements which will be imposed on the scientist and engineer.

From statistics prepared by NASA (Ref. 256) a list of United States and Russian satellites, lunar probes, and space probes during period 1957 to June 1960 is presented; and where known, an indication of their payload instrumentation function is stated. See Table 3-5.

Table 3-6 lists minimum instrumentation requirements for a manned orbital type space vehicle. (Ref. 257). For initial flight tests, the instrumentation system should provide useful and detailed information concerning:

1. The mechanical, aerodynamic, and thermodynamic integrity of the vehicle.

2. The operation of the control, guidance and navigation systems.

3. Environmental factors related to human existence and performance.

4. The psychological and physiological functions of the pilot (passenger).

As the program progresses and many orbital flights with successful returns are made, the function of the instrumentation of the vehicle will change. Accumulating engineering, physiological, and psychological data will, for the greater part, be changed to monitoring the integrity of the space vehicle and the well-being of man. As basic information is gained and new problems are encountered, new instrumentation requirements will be added. For some time to come, however, each trip or orbit can be considered a new exploration.

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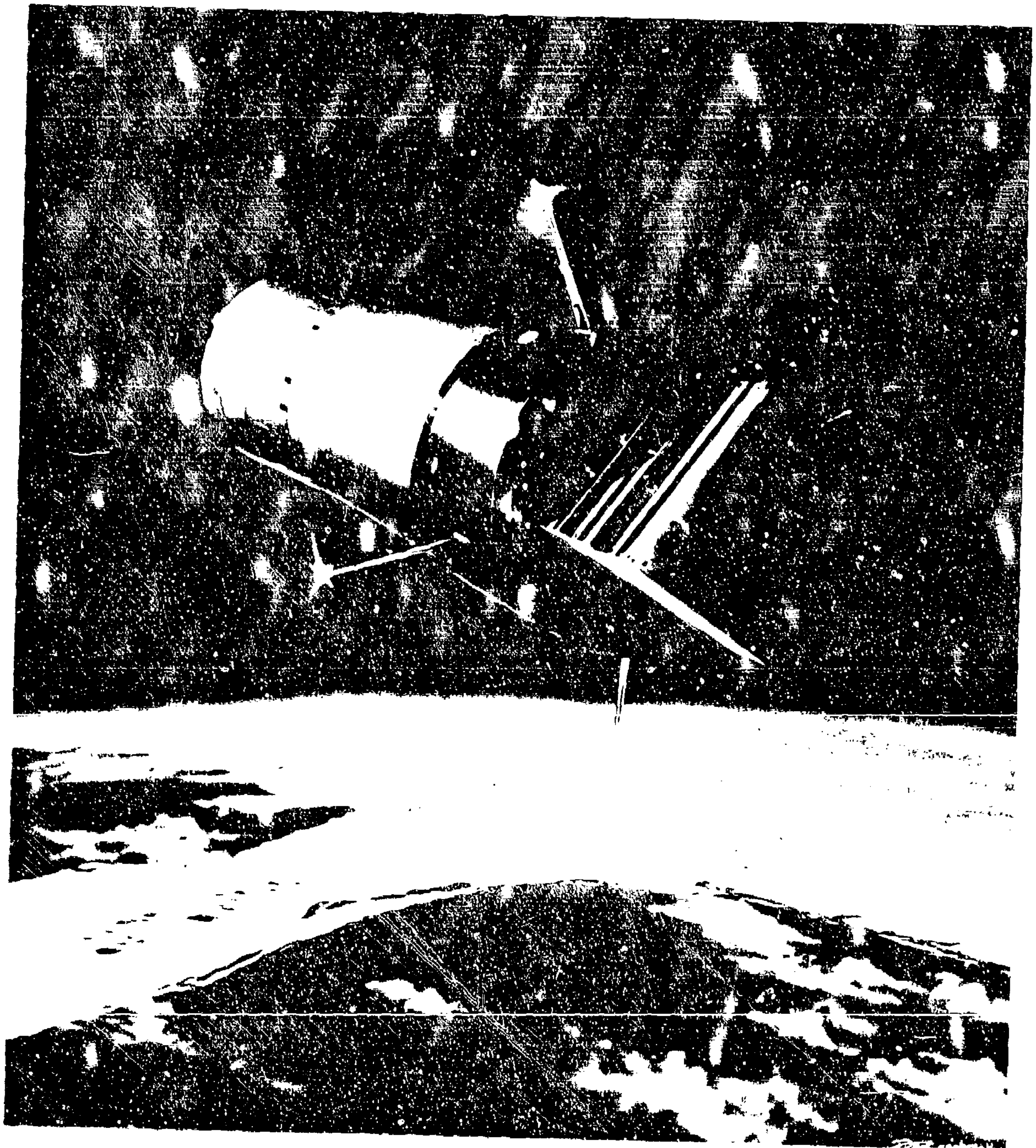
256 NASA Authorization for Fiscal Year 1962, Part 2

257 Ellis, A. B., "An Airborne Data Collection, Telemetering and Ground Data Processing System for Development Flight Test of an Orbital Type Space Vehicle." National Telemetering Conference, 1960



NASA PHOTO NO.
61-M-Scout-4

Fig.3-10 This is an artist's conception of the Mercury-Scout 1 satellite built to test Project Mercury's world-wide tracking network. The cigar-shaped vehicle contains transmitting and receiving equipment similar to that used in Mercury spacecraft.

Table 3-5 United States and Russian Satellites Lunar Probes and Space Probes, 1957 to June 1960, (obtained from statistics prepared by the National Aeronautics and Space Administration)

Name	Type	Scientific Instrumentation Weight In lbs.	Experiments	Results
Sputnik I	Russian Satellite	184	Internal temperatures, pressures, and other data.	
Sputnik II	Russian Satellite	1120	Cosmic rays; solar ultraviolet and X-radiation; test animal "Laika" (dog); temperatures: pressures.	The available acceleration of this satellite led to the discovery of significant solar influence on upper atmosphere densities
Vanguard (test vehicle 3)	United States Satellite	3.25	Micrometeor impact and geodetic measurements.	Vehicle lost thrust after 2 secs. and was consumed in flames.
Explorer I	United States Satellite	18.13	Cosmic rays; micrometeorites: (a) microphone; (b) gages; temperatures: internal, rear skin, front skin, and nose cone.	Explorer I is credited with what is probably the most important satellite discovery of the International Geophysical Year; i.e., a radiation belt around the Earth identified by Dr. James A. Van Allen, head of the University of Iowa Physics Department.
Vanguard (test vehicle 3 backup)	United States Satellite	Same as Vanguard (test vehicle 3)		After a successful liftoff and 57 sec. of flight, a connection between units of 1st stage control system failed to function.
Explorer II	United States Satellite	18.83	Cosmic ray count; micrometeor impact count; cosmic ray measurement.	Last stage failed to ignite. Vehicle did not achieve orbit.
Vanguard I	United States Satellite	3.25	Temperatures and geodetic measurements.	The solar-powered radio should transmit indefinitely. The satellite is being used for more exact determination of the Earth's shape.
Explorer III	United States Satellite	18.56	Cosmic rays with tape-recorder feature; micrometeor gages; temperatures, (a) skin and (b) internal.	Explorer yielded valuable data on the radiation belt discovered by Explorer I as well as data on micrometeor impacts (density of cosmic dust) and internal and external temperature of the satellite.
Vanguard (test vehicle 5)	United States Satellite	21.5	Measure X-radiation from the sun.	Component malfunction caused failure and 2d and 3d stages impacted 1,500 miles from launch site.

Name	Type	Scientific Instrumentation Weight In lbs.	Experiments	Results
Sputnik III	Russian Satellite	2,925	Atmospheric pressure and composition; concentration of positive ions; satellite's electrical charge and tension of earth electrostatic field; tension of earth's magnetic field; intensity of sun's corpuscular radiation; composition and variations of primary cosmic radiation; distribution of photons andheavy nuclei in cosmic rays; micrometeors; temperature measurements.	
Vanguard vehicle 1 (no name)	United States Satellite	21.5	Solar Lyman-Alpha radiation and space environment.	Malfunction caused failure. 3d stage of satellite reached peak altitude of 2 200 miles and traveled 7,500 miles from Cape Canaveral, landing near east coast of Union of South Africa.
Vanguard (SLV2) (no name)	United States Satellite	21.5	Measurements of X-radiation from the sun.	Second stage motor cut off prematurely due to low chamber pressure and terminated the flight.
Explorer IV	United States Satellite	25.8	Two Geiger-Mueller counters and 2 scintillation counters to measure corpuscular radiation at several intensity levels. The subcarrier oscillator was calibrated to give internal temperature measurements.	Valuable data on radiation belts was acquired.
No name	Untied States Lunar probe	25	Measurements of radiation in space; magnetic fields of Earth and Moon; density of micrometeoric matter; internal temperatures; electronic scanner.	Engine failure in 1st stage caused vehicle blow up 77 seconds after launch.
Explorer V	United States Satellite	25.8	Measurement of corpuscular radiation at several intensity levels.	Orbit was not achieved, flight time: 699 seconds.
Vanguard (SLV 3)	United States Satellite	21.5	Two infrared photocells to scan earth's cloud cover.	It is believed to have made 1 complete orbit of Earth before falling back and burning up over central Africa.
Pioneer I	United States Lunar probe	39	Measurements of radiation in space; magnetic fields of Earth and Moon; density of micrometeor matter; internal temperatures; electronic scanner.	First observation that radiation is a band. Mapped total ionizing flux. 1st observation of hydromagnetic oscillations of magnetic field of Earth. Discovered departure of magnetic field from theoretical prediction. 1st determination of the density of micrometeors in interplanetary space. 1st measurements of the interplanetary magnetic field.

Table 3-5-- Continued

Name	Type	Scientific Instrumentation Weight In lbs.	Experiments	Results
Beacon	United States Inflatable Satellite	9.26	Ejection of sphere from payload package; sphere itself would be used to study atmospheric density at various levels during lifetime of about 2 weeks.	Part of the cluster, including payload, separated from the booster prior to booster burnout.
Pioneer II	United States Lunar probe	34.3	Total ionizing radiation; cosmic ray flux; magnetic fields of Earth and Moon; density of micrometeoric matter; internal temperatures; electronic scanner.	3d stage failed to ignite. Evidence that equatorial region about Earth has higher flux and higher energy radiation than previously considered. Suggestion that micrometeor density is higher around Earth than in space.
Pioneer III	United States Space probe	12.95	Measurement of radiation in space.	Discovered 2d radiation belt around Earth.
Project Score (Atlas)	United States Satellite	150	Twin packages of radio transmitting, recording, and receiving apparatus, each weighing 35 lbs.	1st time a human voice has been beamed from outer space.
Lunik or Mechta (Dream)	Russia Space probe	3,245	Instruments to measure temperature and pressure inside vehicle; instruments to study gas components of interplanetary matter and corpuscular radiation of the Sun; magnetic fields of Earth Moon; meteoric particles in space; heavy nuclei in primary cosmic radiation and other properties of cosmic rays.	In orbit around Sun on 15-mo. cycle.
Vanguard II	United States Satellite	20.5	Cloud cover.	In general the satellite and its instrumentation functioned as planned. However, interpretation of cloud cover data has been difficult because satellite developed a wobbling (precessing) motion.
Discoverer I	United States Satellite	245	Check out propulsion, guidance, staging, communications.	Difficulty in stabilization caused tumbling which hampered consistent tracking acquisition.
Pioneer IV	United States Satellite	13.40	Measurement of radiation in space. Test photoelectric sensor in vicinity of Moon.	Probe achieved its primary mission, an Earth-Moon trajectory, yielded excellent radiation data and provided a valuable tracking exercise. While the probe reached the vicinity of the Moon, it did not come close enough (20,000 miles) to trigger photoelectric sensor or sample Moon's radiation.

Table 3-5--Continued

Name	Type	Scientific Instrumentation Weight In lbs.	Scientific Instrumentation Experiments	Results
Discoverer II	United States Satellite	1,610	To recover capsule; maintain temperature and oxygen sufficient to sustain life; emulsion packs to measure radiation.	All equipment worked as programed except timer which ejected capsule. Capsule, which contained radiation emulsion packs, has not been found.
Vanguard	United States 2 Satellites	23.3	Vanguard 3A contained a precise magnetometer to be used to map Earth's magnetic field. Vanguard 3B was to measure drag in space.	2d stage failed to operate properly which caused a tumbling motion. Payload and 3d stage fell into Atlantic Ocean.
Discoverer III	United States Satellite and nose cone re-entry capsule.	440	Measurement of cosmic radiation, biomedical environmental research, and capsule recovery techniques by C-119 aircraft patroling recovery area.	Tracking stations did not receive telemetry from satellite; doubtful it achieved orbit.
Vanguard (SLV-6)	United States Satellite	22.5	Measurements of solar-earth heating process which generates weather.	A faulty 2d stage pressure valve caused failure, and it plunged into Atlantic Ocean some 300 miles northeast of Atlantic Missile Range.
Discoverer IV	United States Satellite and nose cone re-entry capsule.	1,700	Capsule contained telemetry equipment to measure its performance	Failed to achieve orbit. Insufficient velocity caused failure to orbit.
Explorer	United States Satellite	91.5	Measurements of (1) earth's radiation balance, (2) Lyman-alpha X-rays, (3) heavy primary cosmic rays, (4) micrometeorites, (5) cosmic rays, (6) satellite temperature, and (7) erosion study of exposed solar (silicon) cell on outside of satellite.	Vehicle was destroyed by range safety officer after 5 1/2 secs. when it tilted sharply.
Explorer VI	United States Satellite	142	(1) Measurement of 3 specific radiation levels of Earth radiation belt; (2) TV-like scanning device to relay cloud cover picture; (3) solar cells (8,000 in all; 1,000 on each side of 4 paddles) to create voltage to recharge the satellite's chemical batteries in flight (electronic gear in satellite includes 3 transmitters and 2 receivers); (4) micrometeorite detector; (5) 2 types of magnetometer to map Earth's magnetic field; (6) 4 experiments to study behavior of radio waves, all aimed at learning more about deep space communications.	Valuable data transmitted on distribution of dust particles and concentration of low-energy particles.
Discoverer V	United States Satellite and nose cone re-entry capsule.	1,700	Same as Discoverer IV.	Satellite went into orbit, all equipment working as programed. However, reentry capsule was not recovered due to malfunction following its ejection from satellite.

Table 3-5--Continued

Name	Type	Scientific Instrumentation Weight In lbs.	Experiments	Results
Beacon	United States Satellite	25.8	Inflatable satellite of Mylar plastic film and aluminum foil. Satellite itself contains no instrumentation.	Payload failed to achieve orbit due to premature fuel depletion in booster and malfunction in attitude control system for upper stages.
Discoverer VI	United States Satellite and nose cone re-entry capsule.	1,700	Same as Discoverer IV.	Same as Discoverer V.
"Lunik II"	Russia: Lunar probe	858.4	Instruments to measure temperature and pressure inside vehicle; instruments to study magnetic fields of Earth and Moon; metoric particles in space; heavy nucleii in primary cosmic radiation and other properties of cosmic rays.	58.4-lb. lunar probe hit surface of the Moon at 5:02:24 p.m. e.d.t. 1 min. 24 sec. later than predicted by Russia scientists.
Transit I-A	United States Satellite	265	Transmitters: (a) 54 mc.; (b) 162 mc.; (c) 216 mc.; all at 100 mw.	Satellite failed to achieve orbit, the 3d stage did not fire.
Vanguard III (SLV-7)	United States Satellite	50	Measurements of earth's magnetic field, solar X-rays, and environmental conditions in space.	Provided comprehensive survey of Earth's magnetic fields over area covered; detailed location of lower edge of Van Allen Radiation Belt; accurate count of micrometeors.
Lunik III	Russia translunar earth satellite	614	Two cameras, developing mechanism and automatic devices for triggering cameras, developing processes and transmission pictures to earth. Also automatic temperature control mechanism. Other experiments not disclosed.	When satellite was about 40,000 miles from Moon's surface, the cameras were triggered. They produced photographs of high precision showing 70 percent of Moon's backside. Cameras were operated on Oct. 7, 1959, for 40 mins. Pictures were transmitted to Earth shortly before reaching perigee on Oct. 18, 1959.
Explorer VII	United States Satellite	91.5	Radiation balance; Lyman-alpha X-ray; heavy primary cosmic ray; micrometeorite; cosmic ray; exposed solar cell; temperature measurements.	Provided significant geophysical information on radiation and magnetic storms; demonstrated method of controlling internal temperatures; first micrometeorite penetration of a sensor in flight; detection of large-scale weather patterns.
Discoverer VII	United States Satellite and nose cone re-entry capsule.	1,700	Same as Discoverer IV.	Satellite went into orbit, however, reentry capsule was not released due to malfunction of electrical system and possible lack of stabilization.

Table 3-5--Continued

Name	Type	Scientific Instrumentation Weight In lbs.	Experiments	Result
Discoverer VIII	United States (ARPA)	1,700	Same as Discoverer IV.	Satellite went into orbit, however, although reentry capsule was ejected it was not recovered and search was abandoned.
Pioneer	United States Lunar probe	372	To obtain basic measurements of the lunar environment. (1) Measurements of 3 specific energy levels of cosmic rays; (2) TV-like scanning device to relay lunar surface picture; (3) solar cells (8,800 in all; 1,200 on each side of 4 solar vanes to create voltage to recharge the probe's chemical batteries in flight (Note: Electronic gear in probe includes 2 transmitters and 2 receivers); (4) micrometeorite detector; (5) 2 types of magnetometer; (6) radio wave experiments.	Malfunction in 2nd stage guidance started failure and satellite did not go into orbit.
Discoverer IX	United States Satellite and nose cone reentry capsule.	1,700	Launching technique, propulsion, communications, orbital performance, recovery techniques, and advanced engineering tests.	Vehicle rose from pad as programed. Telemetry was lost soon afterward. Radar showed that the Discoverer failed to achieve orbital velocity and fell back to Earth.
Discoverer X	Same as Discoverer IX	Same as Discoverer IX.		Vehicle rose from pad as programed but veered off course at 20,000 ft. and headed for nearby seacoast cities. Range safety officer destroyed vehicle 52 sec. after launch.
Midas (Missile Defense Alarm System) I	United States Air Force	4,500	Payload: Infrared, telemetry, communications, and other advanced engineering test equipment. Experiments: To establish workability of the Atlas-Agena combination, launch procedure, and tracking and communications systems. The Midas program is designed to detect heat radiating from the exhaust of ballistic missiles and to feed detections into the air defense warning net.	It is presumed that 2d stage separation did not occur and the vehicle burned up upon reentering the atmosphere about 2,500 miles downrange from Cape Canaveral.
Pioneer V (1960 Alpha)	United States space probe	40	Mission: To provide information about space between the orbits of Venus and Earth; to test the feasibility of long-range interplanetary-type communications; and to improve methods for measuring astronomical distances. Experiments: Measurements of radiation, magnetic fields, micrometeoroid activity, and temperatures.	Many "firsts" in long range communications, gauged solar flare effects, particle energies and distribution, and magnetic field phenomena in interplanetary space.

Table 3-5 Continued

Name	Type	Scientific Instrumentation Weight In lbs.	Experiments	Results
Explorer	United States Satellite	12.19	Mission: To analyze the energies of electron and proton radiation in the Van Allen Radiation Zones. Experiments: Detailed measurements of energetic particles in the Van Allen Radiation Zones and of temperatures inside and outside the payload.	Ground stations lost communications with the vehicle after 2d stage burnout.
Tiros (Television and Infra-Red Observation Satellite) I (1960 Beta)	United States meteorological satellite	270	Experiments: 2 TV systems--1 wide angle, 1 narrow angle, photograph cloud cover and transmit images to Earth. Other instruments: Telemetry, command and an attitude sensor system.	Because of an apparently inoperative relay, interrogation was ceased June 28, 1960, after reception of 22,952 highly successful cloud cover photographs.
Transit I-B (1960 Gamma)	United States Navy satellite	265	Satellite instruments: (a) 2 ultra-stable oscillators (radio frequency generators) in temperature-resistant Dewar flasks. Each oscillator can transmit on 2 frequencies. (b) Infrared scanner to measure satellite's rotation. (c) 2 receivers. (d) 2 telemetering gathering and sending devices. Experiment: To determine the feasibility of and improve equipment for providing a global all-weather navigation system that is more reliable than systems now in use under any weather conditions. Such a system would enable ships and aircraft to locate precisely their positions on earth regardless of weather.	In orbit April 13, 1960, with estimated life of 16 months.
Discoverer XI (1960 Delta)	United States Satellite and nose cone re-entry capsule.	1,700	Same as Discoverer IX except that about 10 lbs. of instruments were installed in the 2d stage casing (satellite) for a tracking experiment connected with the Transit development program. The Transit instrument package consists of a Doppler beacon and external lights for optical tracking by Baker-Nunn cameras of the Smithsonian Astrophysical Observatory. (See Transit 1-B.) Discoverer program objectives are to gather data on satellites and their behavior, on stabilization of a satellite in orbit, and on techniques of recovering objectives that have gone into orbit.	2d stage casing with capsule went into Polar orbit. Capsule was ejected. The capsule was not observed as descending into the recovery area, and recovery was not attempted.
Echo	United States	240	Telemetry beacon in 3d stage; casing designed to follow sphere into orbit. Operating at 108.06 mc, continuous for 6 to 10 days (est.) at 60 mw; powered by Mercury batteries; designed as passive communications satellite with aluminum coating to provide radio wave reflectivity of 98 percent up to frequencies of 20,000 mc.	Did not achieve orbit due to apparent malfuction in the attitude controls on 2d stage and failure of 3d stage to receive ignition signal.

Table 3-5--Continued

Name	Type	Scientific Instrumentation Weight In lbs.	Scientific Instrumentation Experiments	Results
Sputnik IV (1960 Epsilon) "Spacecraft"	Russia	10,008	A 2-part craft with undisclosed shape and dimensions. "Dummy spaceman" with environmental control system. 19.995 mc transmitter for both telemetry and "telephone" systems. Tape of voice transmitted to ground stations.	Launch and near circular orbit achieved. After retrorocket firing on May 19, 1960, pressure vessel apparently separated from cabin but due to orientation fault went into lopsided orbit instead of reentering the atmosphere.
Midas II (1960 Zeta)	United States Satellite	5,000	Instrumentation details not released. Includes infrared telemetry and communications equipment.	Orbit achieved. 2 days after launch, data link telemetry transmitting infrared scanner information to ground stations ceased functioning.
Transit II-A (1960 Eta)	United States Navy	223 plus 42 lb. pickaback satellite	Two ultra-stable oscillators; infrared scanner to measure satellite's rotation; electronic clock as time standard; Canadian receiver to measure galactic noise. 42-lb. pickaback satellite with insturments to measure solar radiation and other information on ionosphere.	Two satellites placed in Earth orbit. Both transmitting clearly.
Discoverer XII	Same as Discoverer XI		Same as Discoverer XI, except extra instrumentation was added in an effort to determine the causes of previous Discoverer failures.	Failed to achieve orbit, reentered the atmosphere and burned up over the South Pacific.

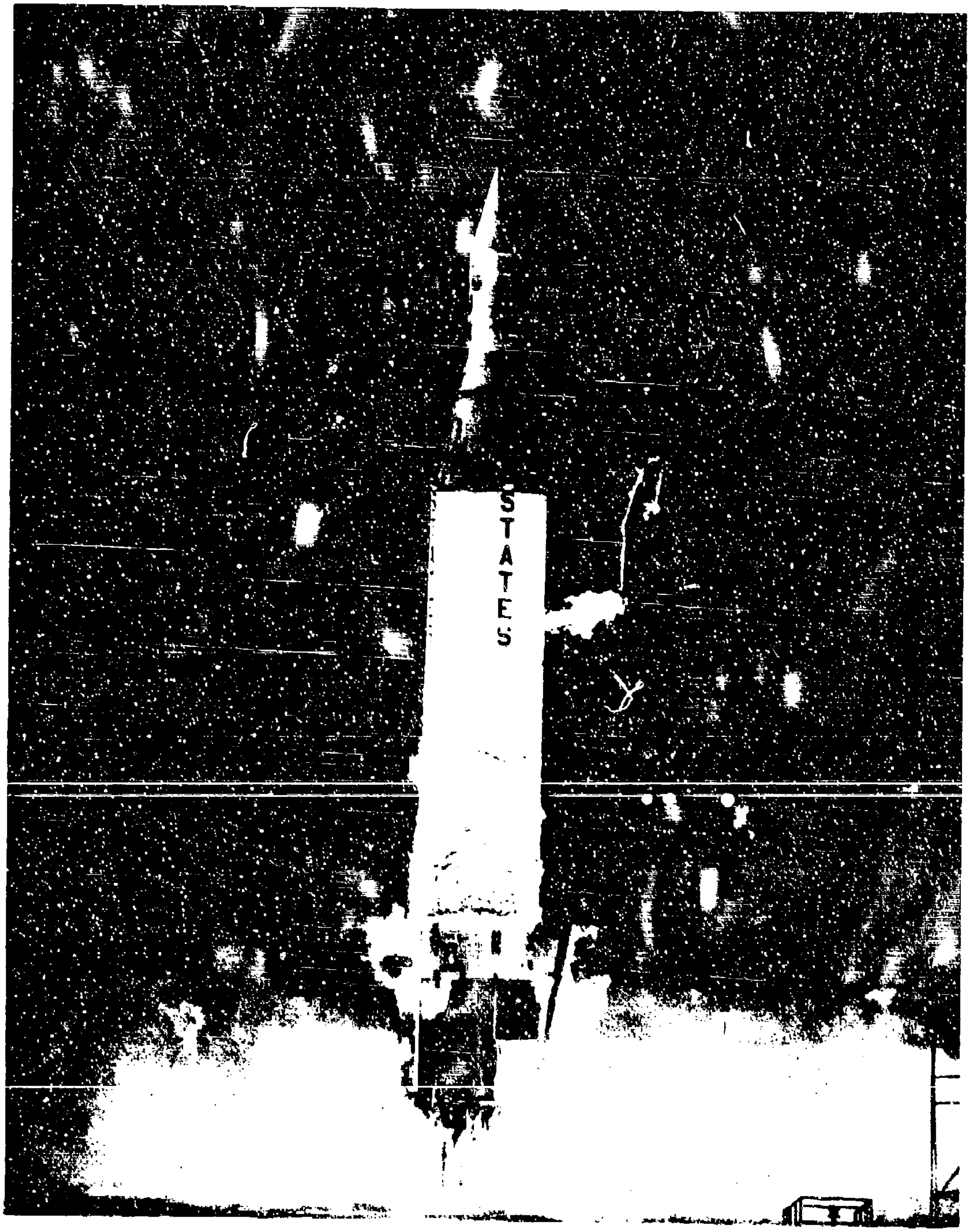


Fig.3-11 Launch of a NASA 4-stage JUNO II Rocket carrying a 90 pound satellite designed to make a direct measurement of the Ionosphere, launched into orbit at 12:23 a.m., EST, Nov. 3, 1960.

Table 3-6 Minimum Instrumentation Requirements for a Manned Orbital Type Space Vehicle

Vehicle Integrity

	Number	Pre-orbit	Orbit	Re-entry
Temperature measurements	M	X		X
Stress and Strain measurements	M	X		X
Vibration and Flutter measurements	M	X		X
Meteorite impact	1		X	

(other factors included below)

System Monitor and Operational Evaluation

	Number	Pre-orbit	Orbit	Re-entry
Pitch Acceleration	1	X	X	X
Body Angular Rates	3	X	X	X
Linear Acceleration (two ranges)	6	X	X	X
Attitude Indications	3	X	X	X
Elevon Positions	2			X
Actuator Pressure	2			X
Control Current to Reaction Units	12		X	
Reaction Jet Valve Position	12		X	
Fuel Rate of Flow	12		X	
Fuel State	1		X	
Command Receiver Signals	P	X	X	X
Outside Air Temperature	1	X	X	X
Outside Air Pressure	1	X	X	X
Stagnation Temperature	2	X		X
Wing Leading Edge Temperature	10	X		X
Position Data	2	X	X	X
Radio Altimeter Signal	1	X	X	X
Programmer Signals	P	X	X	X
Power Supply Voltages	P	X	X	X
Power Supply Frequencies	P	X	X	X
Ram Air Pressure	1			X
Static Air Pressure	1			X
ON-OFF Signals				
Roll Control	1		X	X
Pitch Control	1		X	X

Table 3-6 (continued)

	Number	Pre-orbit	Orbit	Re-entry
Yaw Control	1		X	X
CO_2 Level Warning	1	X	X	X
Cabin Decompassion	1	X	X	X
Attitude Control System Failure	1		X	X
Environmental Control System Failure	1	X	X	X
Electrical System Failure	1	X	X	X
Radiation Warning	1	X	X	
May Day	1	X	X	X

Environmental Factors

	Number	Pre-orbit	Orbit	Re-entry
Cabin Wall Temperature	N	X	X	X
Cabin Air Temperature	1	X	X	X
Cabin Air Pressure	1	X	X	X
Suit Pressure	1	X	X	X
Radiation Rate	1	X	X	X
Humidity (Cabin)	1	X	X	X
Acoustic Pressure (Cabin)	N	X		X
CO_2 Partial Pressure	1	X	X	X
CO_2 Filter Status	1	X	X	X
O_2 Reserve	1	X	X	X

M = Number of measurements determined by test phase and progress of the test.

N = Number of measurements determined by the cabin configuration and progress of test.

P = Number of measurements determined by system configuration.

Table 3-6 Human Factors -- Continuous recording and monitoring

Name	Range
EKG (Electrocardiogram) (2)	0 - 2.5 mv
Respiratory Rate	0 - 60 cpm
Respiratory Depth	0 - 50 cps
Heart Rate	0 - 300 cpm
Heart Sounds	20 cps to 2 kc
EEG (Electro-encephalogram)	0 - 50 cps
GSR (Galvanic Skin Response)	5,000 - 20,000 ohms
Blood Pressure	
Systolic	
Diastolic	
Muscle Activity	30 cps to 5 kc
Eyeball Movement	0 - 10 cps
O_2 Flow Rate	2 - 12 cft/min
Body Temperature (7)	60 - 115° F

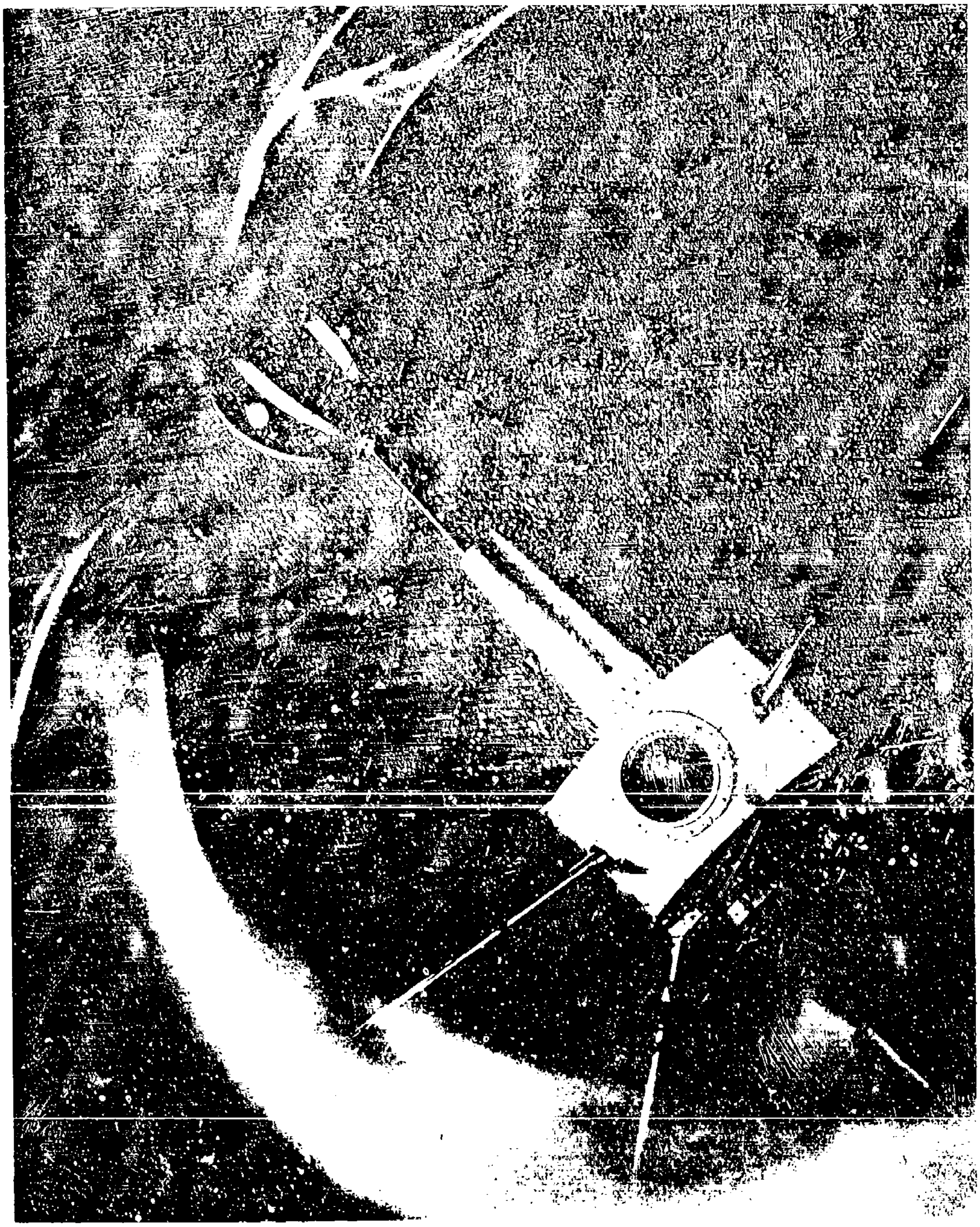


Fig. 3-12 A photographic conception of the 78 pound payload (P-14 Magnetometer-Plasma Probe) on its journey to outer space. The P-14 probe is programmed for a four-day 100,000 mile orbit and return to the edge of the earth's atmosphere. The heart of the payload is a 1.5 pound rubidium vapor magnetometer, two fluxgate magnetometers, weighing about one pound each and a plasma probe, and an optical aspect sensor weighing about 2.5 pounds. The experiment is expected to determine more precisely the nature of the inter-action of magnetic fields and solar corpuscular radiation.

b. Experiments

(1) Erosion, Impact, and Piercing (Ref. 258)

Erosion of a satellite's shell through bombardment by dust, micrometeorites, ions, molecules, and atoms may be recorded by chromium-strip erosion gauges on the satellite's surface. Electrical resistance of the guages changes as their surfaces are changed by erosion. Cadmium-sulphide cells may be used as photosensitive detectors. Such cells, when coated by an opaque covering of Mylar plastic and deposited aluminum, experience resistance changes as the covering is eroded or penetrated. Telemetering the resistance changes permit the estimating or erosion rates.

The ionosphere probe (Ref 259) 1960 Xi (Explorer VIII) carried a micrometeorite photomultiplier experiment using a conventional "end-type" 7151 C photomultiplier with a one-micron evaporated layer of aluminum on the front surface. A micrometeorite particle penetrating the aluminum coating registers its visible-light energy on the photo cathode. The resulting pulse varies in length and amplitude as a function of the micrometeorite's kinetic energy. The maximum sensitivity of the sensor to light pulses is 10^{-3} erg.

Also contained in 1960Xi was a micrometeorite microphone experiment measuring the frequency and momentum of micrometeorite impacts. The micrometeorite targets consisted of two "sounding boards" located on the lower cone of the satellite and acoustically insulated from the satellite skin. Attached to each sounding board was a microphone that detects the impulse that occurs when a micrometeorite collides with the sounding board. By pre-flight calibration the detected impulse may be related to the momentum of the incoming particle.

The Scout S-55 satellite(Ref. 260) will carry five micrometeoroid detectors: pressurized cells, foil gages, wire grids, cadmium-sulfide cells and impact sensors. The impact sensors are piezoelectric crystal impact-detecting transducers acoustically decoupled from satellite structure and have three levels of impact-detecting sensitivity. The cadmium sulfide cells are mounted in

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258 "IGY Satellite 1959 Eta," IGY Bulletin, Number 28, National Academy of Sciences, October 1959, p. 13.

259 "Ionosphere Direct Measurement Satellite," IGY Bulletin, Number 42, December, 1960.

260 From News Item, Electronic Design, September 13, 1961

aluminum flasks. Their exposed surfaces are covered with a sheet of 1/4 mil Mylar, coated with evaporated aluminum on both sides. The foil-gage detectors consist of an electrochemical deposition about 90 microinches on 1-mil Mylar and mounted to 304 stainless-steel samples of rocket skin. The wire grids consist of 46 windings of fine copper wire mounted on 1.45 x 7 inch rectangular melamine cards. The pressure cells are the primary sensors of the probe. They are beryllium copper detectors composed of 160 half-cylinders from 0.1000 inch to 0.5000 inch thick.

Conventional pressure transducers may be used to record the impact of micrometeorites which are large enough to penetrate the shell or special skin area of a satellite. Hermetically sealed pressure zones would be placed to girdle an area of the interior wall. These zones would be pumped down to partial vacuums, each at a different pressure. With differential pressure transducers connected to each pair of zones, data would be generated indicating which zone is punctured.

The 1960 Alpha (Pioneer V) carried a device (Ref. 261) to record micrometeorite impacts and later relay the indication to the earth. This device developed by the Air Force Cambridge Research Center consisted of a diaphragm about twice the size of a playing card mounted on the payload skin and connected to a microphone. The noise of impact on the diaphragm is translated to an electrical impulse which is recorded with other signals and later relayed via telemetry system to the earth.

The 1959 Eta (Vanguard III) carried a microphone-impact counter system (Ref. 262) utilizing four piezoelectric transducers attached to the metallic skin of the satellite. The resulting electrical impulses from impacts triggered a three-digit, magnetic core, decimal counter. A tone-burst indicating the count of each decade of the counter was sent via telemetry system. Care must be employed in counting systems to insure against false triggers resulting from electrical noise in satellites electronics or deterioration from environmental (temperature, radiation etc.) effects.

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261 "Pioneer V Space," IGY Bulletin, Number 34, April, 1960.

262 "Satellite Measurements of Cosmic Dust," IGY Bulletin Number 38, August, 1960.

(2) Magnetic Field Measurements (Ref. 263)

Charting the earth's magnetic field in space is of special importance to future manned space explorations since such charts will indicate the best routes to avoid regions of intense radiation trapped in the magnetic field. In addition, space measurements of the magnetic field will aid in a better understanding of magnetic storms. These solar-related storms render virtually useless many devices which rely on the magnetic field, such as the magnetic compass, and surveying and navigational instrumentation.

Magnetometers are used in the measurement of the earth's magnetic field. The 1959 Eta (Vanguard III) carried a magnetometer which consisted of a copper coil filled with hexane located in the tip of the magnetometer tube. Wires connect the coil to electronic equipment and batteries in the satellite sphere. On command from a ground station, the coil is energized by 6.5 amperes of electrical current for about two seconds. This, in turn, orients the protons (H+) in the liquid and causes them to spin within the coil in a prescribed manner.

After the current flow stops the protons spin for another 2 to 2.5 seconds in wobbling orbits in a manner dictated by the characteristics of the earth's magnetic field. The frequency of the proton motion imparts voltage to the coil. This voltage is then amplified and transmitted instantaneously to a ground receiver where it is taped. Simultaneously a reading is made at the ground magnetometer with which each of the interrogating stations is equipped.

The 1960 Alpha (Pioneer V) satellite carried a one-pound search coil magnetometer developed by STL. This instrument was designed to determine the strength and direction of magnetic fields in space.

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263 "IGY Satellite 1959 Eta," IGY Bulletin, Number 28, National Academy of Sciences, October 1959, p. 13.

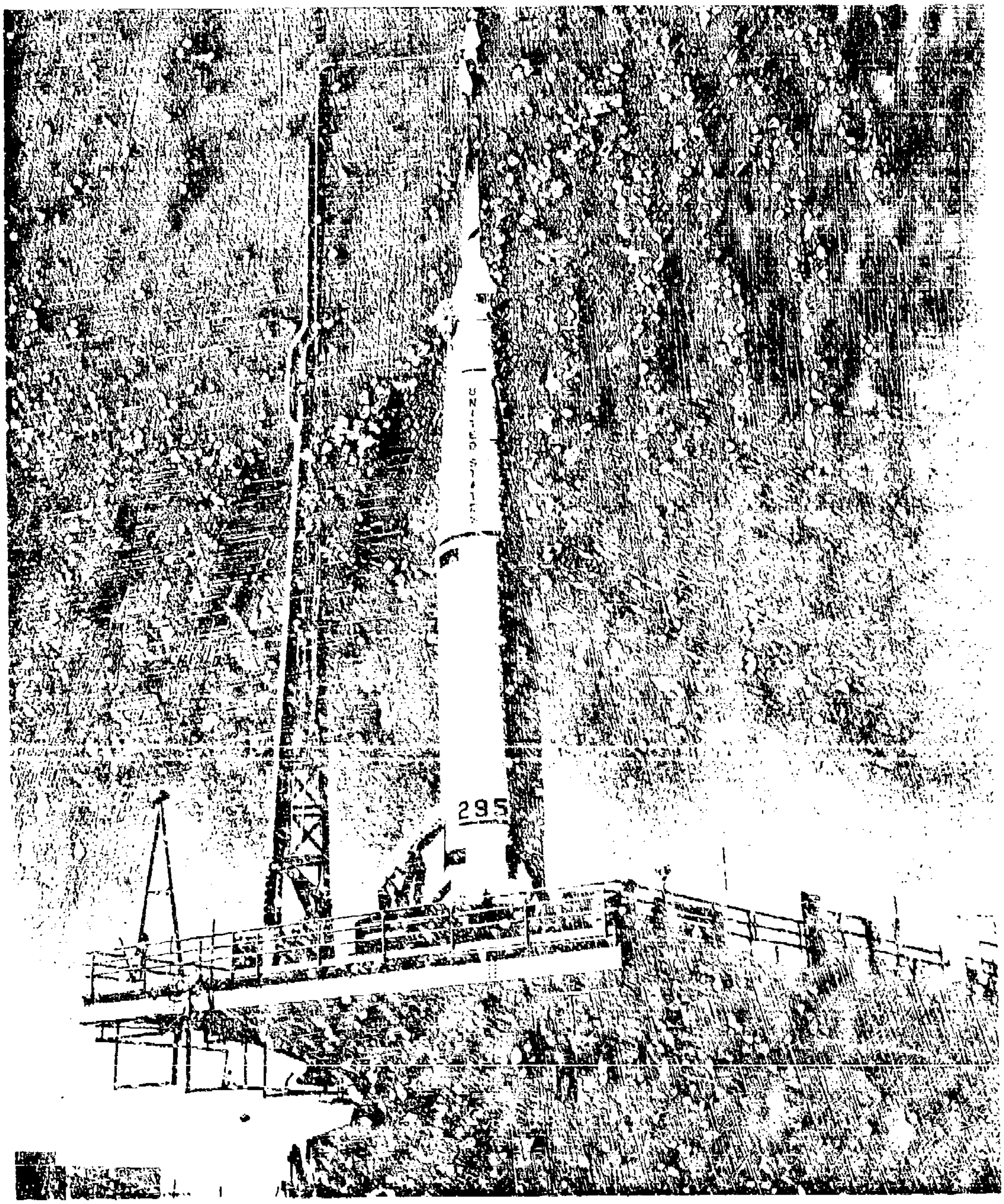
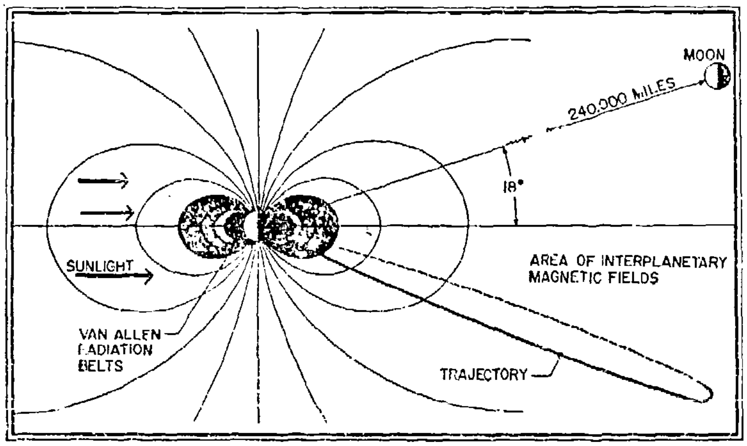


Fig. 3-13 A Thor-Delta Launch Vehicle being readied to project a space probe, designed to gather the most definite information yet obtained, on earth and inter-planetary magnetic fields, and the way these fields effect and are effected by solar-plasma. The 92 foot launch vehicle will project a 78 pound payload toward a four-day flight outward in a highly eccentric earth orbit to a distance of over 100,000 statute miles and back to the edge of the earth's atmosphere.

On March 25, 1961, satellite 1961 Kappa (Pioneer X) was launched (Ref. 264) see Figure 3-14 of planned orbit. It was the first flight into deep space with a highly accurate rubidium-vapor magnetometer. The Explorer X model measures field intensities ranging from .01 to 7000 gammas. It is absolute reading instrument in that its measurements depend only on fixed constants that do not require calibration.



Planned Trajectory of Explorer X. The satellite's actual orbit was very close to that shown, providing the desired relative positions of earth, sun, moon, and satellite. NASA photograph.

Figure 3-14

The rate at which the outer Rb-87 electron revolves around its nucleus is known precisely and would produce a frequency of nearly 7 cycles per second in a weak magnetic field of 0.00001 gauss. The frequency is directly proportional to the field strength - i.e., the stronger the field, the higher the frequency.

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264 "Explorer X Magnetic-Field and Plasma-Probe Satellite," IGY Bulletin, Number 48, June, 1961.

This is the way the rubidium-vapor magnetometer works: Light from a small rubidium lamp passes through a filter, lens, and polarizer, and polarized light at a wave length of rubidium then passes into a cell containing rubidium vapor. The light is absorbed by those rubidium -87 atoms having a particular orientation in the cell. When this occurs, the cell becomes opaque to the passage of light, which is detected with a silicon photocell whose output is fed to an amplifier.

As the opaqueness exists for only one-half cycle of the spin of the rubidium atoms, the cell is alternately opaque and transparent at the spin frequency which is determined by the strength of the magnetic field. This produces a fluctuating light at the photocell which is then amplified and fed back as a small alternating magnetic field, which produces an ordered alignment of the rubidium atoms such that the process will be self-continuing.

The 1961 Kappa also carried two fluxgate magnetometers weighing about one pound each and considerably more sensitive than those flown in previous satellites. They are intended to measure fields from 0.5 to 25 gammas and to determine, primarily, the direction of weak magnetic fields. The fluxgate magnetometers are oriented on the payload at a specific angle, such that the spin of the payload makes it possible also to obtain total-field measurements.

An 83-pound spacecraft designated as S-3 will carry a magnetometer package containing three orthogonally mounted saturable core magnetometers with calibration coils. The field effects from densely packed electronics and instruments will be considerably reduced. (Ref. 265)

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265 Same as Ref. 260.

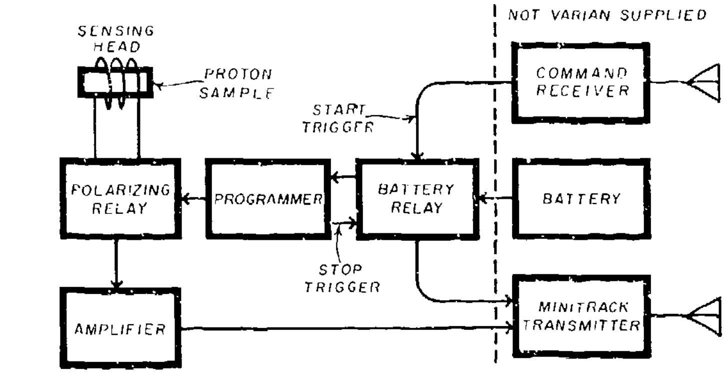

Figure 3-16 Block Diagram X-4942, Proton Magnetometer

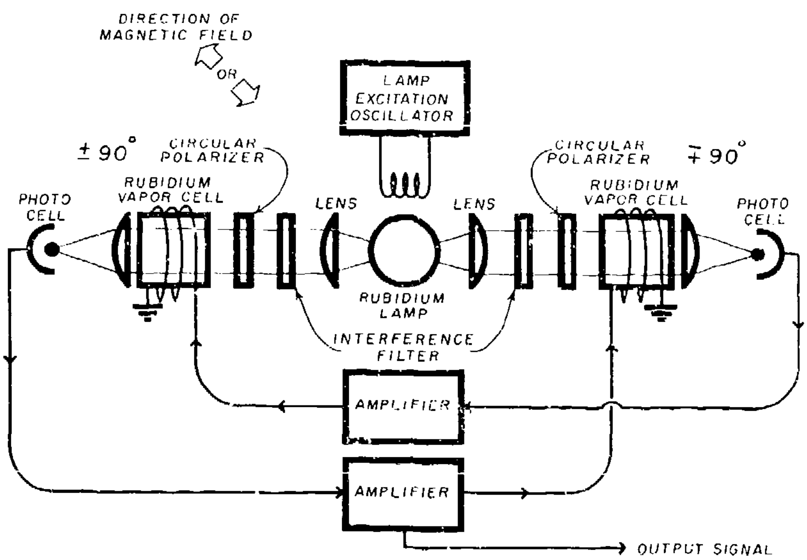

Figure 3-17 Block Diagram-Rubidium Vapor Magnetometer

S-3 ENERGETIC PARTICLES SATELLITE

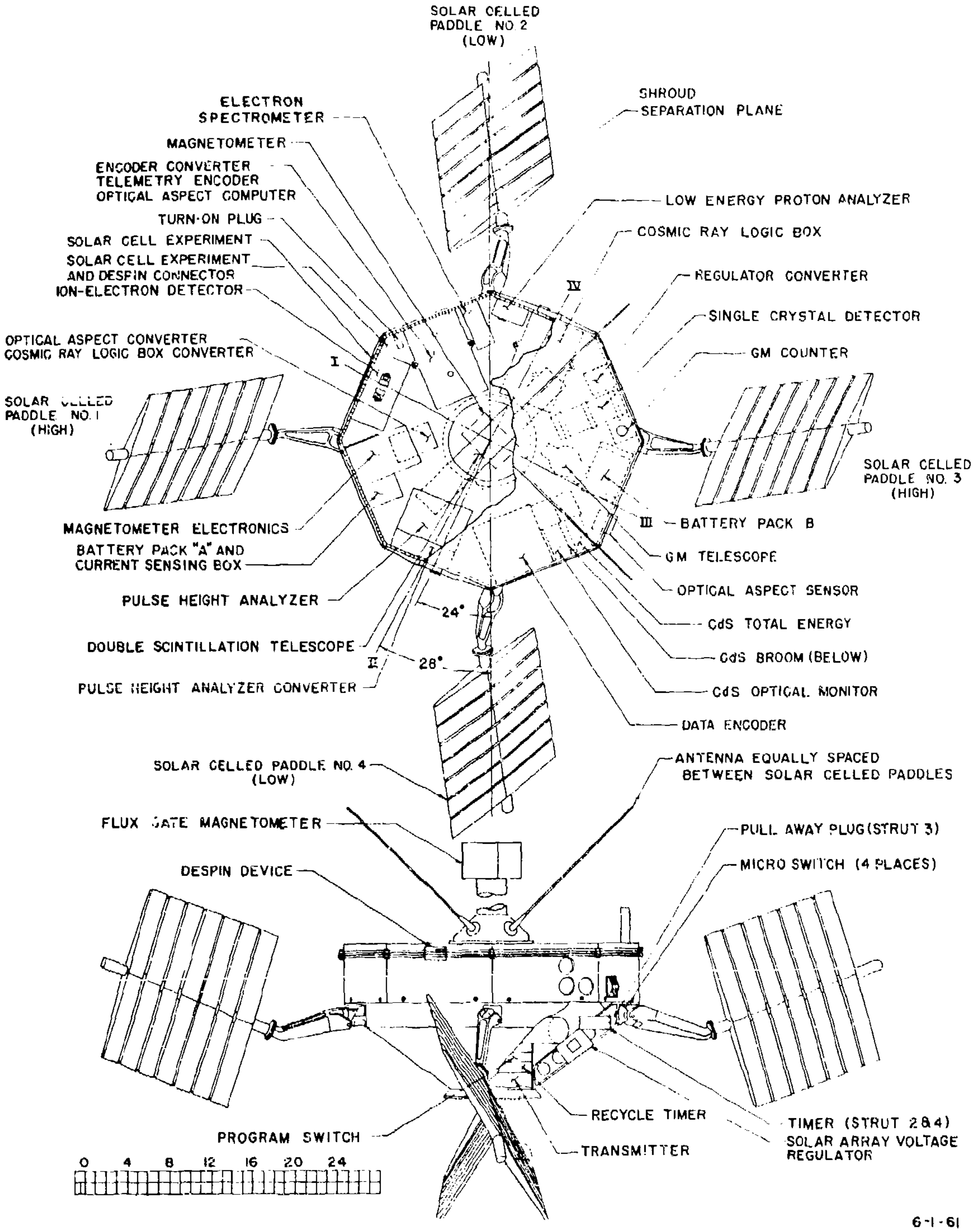

Figure 3-15

The Varian Associates Geophysics Technical Memorandum No. 8 discusses magnetometer applications in space probes. A table (3-7) of specifications is presented indicating various types and their usage. (Ref. 266)

Table 3-7 **TABLE OF SPACE MAGNETOMETER SPECIFICATIONS**

	X-4940	X-4942	X-4945	X-4944	X-4948
1. SAMPLE	Kerosene and Oil	Hexane	Rb^{85}	Rb^{87}	Rb^{87}
2. FIELD OPERATION:					
a. Range (gammas)	12,000 - 52,000 or ± 6,000	12,000 to 52,000	5,000 to 54,000	3 to 10,000	7 to 110
b. Objective Sensitivity (gammas)	5	1	5	1	1 - 0.1
c. Actual Sensitivity (gammas)	2	0.6	0.02	0.02	—
3. TOTAL POWER (watts)	Maximum Duty Cycle is 50%; 102 during polarization	Maximum Duty Cycle is 50%; 102 during polarization	8.0	6 2	3.5
4. OPERATING LIFE (hours)	1	4300 cycles in 85 days	500	1500	5000
5. DIMENSIONS:					
a. Instrument Volume* (cubic inches)	136	92	382	88	59
b. Total Weight (pounds)	6	2 7	6.5	2.6	1.9
6. ORIENTATION DATA:					
a. Optimum Angle of Sensor Axis and Total Field	Omnidirectional	90°	45°	45°	45°
b. Dead Zones	None	5° polar	20° polar 10° equator	15° polar 10° equator	15° polar 10° equator
7. FLIGHT DATA:					
a. Dates	Since July '56	Sept. '59	Dec. '60	March '61	August '61
b. Vehicle	Aerobee; Aerobee Hi	Vanguard III	Javelin	Thor-Delta	Atlas-Agena
c. Altitude or Orbit (miles)	103 to 300	2200/320	717	145,000	600.000 (est.)
d. Field Encountered (gammas)	20,000 to 70,000	7,000 to 16,000	30,400 to 57,000	Not available as yet	

(3) Electromagnetic Radiation Measurements (Infrared, Visible and Ultraviolet)

A great amount of special instrumentation carried in space probes employ electromagnetic radiation sensors in the range of infrared, visible and ultraviolet. Some devices use these sensors in relating characteristics of the space probe (orientation, spin rate, roll, yaw, etc.) in its flight, and other devices measure presence and amount of such radiation in the changing environment of the space probe. The radiation sensing elements can normally be classified under two types: (Ref. 267) those responding to optical radiation, and those based on non-producing effect. Scintillation counters and Cerenkov counters may be considered systems combining the two types. Infrared, visible and ultraviolet sensing elements are normally of the optical radiation type.

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266 Geophysics Technical Memorandum, No. 8, Varian Associates.

267 Same as Reference 120, Chapter 5.

(a) Radiation Balance Measurements (Ref. 268)

The 1959 Iota satellite carried experimental equipment for the study of the thermal radiation balance which is thought to greatly influence the earth's weather. Near the equator, the earth receives more energy from the sun than it radiates into space; conversely, it radiates more energy into space in polar regions than is received there from the sun. The transfer of energy from lower latitudes to higher latitudes is being studied by measuring direct radiation from the sun; the fraction of this radiation diffusely reflected by the earth, clouds and atmosphere; and the fraction of radiation which is converted into heat by the earth and ultimately re-radiated back into space in the far infra-red portion of the spectrum.

Six sensing elements were used: two hemispheres and one sphere painted black to measure total energy at all wavelengths; one hemisphere painted white to measure radiation of longer wavelengths while reflecting shorter wavelengths; and two sensing elements with a special coating to measure short wavelengths only. The black and white sensors were short about one and one-quarter inch in diameter and the elements with a special coating were about one inch in diameter. Each sensor contained a thermistor for temperature measurements.

Figure 3-18 shows a block diagram of the instrumentation used aboard the 1959 Iota satellite, including the heat balance experiment (Ref. 269).

(b) Ultraviolet Measurements

Solar ultraviolet radiation has been measured on the 1960 Eta 2 satellite using Lyman-alpha ionization chambers (Ref. 270). They were cylindrical in shape with a diameter of 3.4 cm and length of 2.4 cm. Each chamber was fitted with a lithium fluoride window and filled with nitric oxide (NO) at a pressure of 15 mm of mercury (Hg). The detectors have a quantum yield, or photoelectric efficiency, of the order of 30% and are sensitive to wavelengths between 1040A and 1340A; the first is determined by the transparency of the lithium fluoride and the second by the ionization potential of the nitric oxide gas. In this wavelength range, Lyman-alpha radiation is the predominant solar emission and contributes all but 10% of the ion-chamber response.

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268 "IGY Satellite 1959 Iota," IGY Bulletin, No. 29, National Academy of Sciences, November 1959, p. 13.

269 King, Olin B., "Signal Processing Explorer VII," IRE Transactions, Fifth National Symposium, 1960, on Space Electronics and Telemetry, Sept. 1960, Section 4-2, p. 10.

270 "Solar Radiation Satellite," IGY Bulletin, No. 42, National Academy of Sciences, December 1960, p. 2.

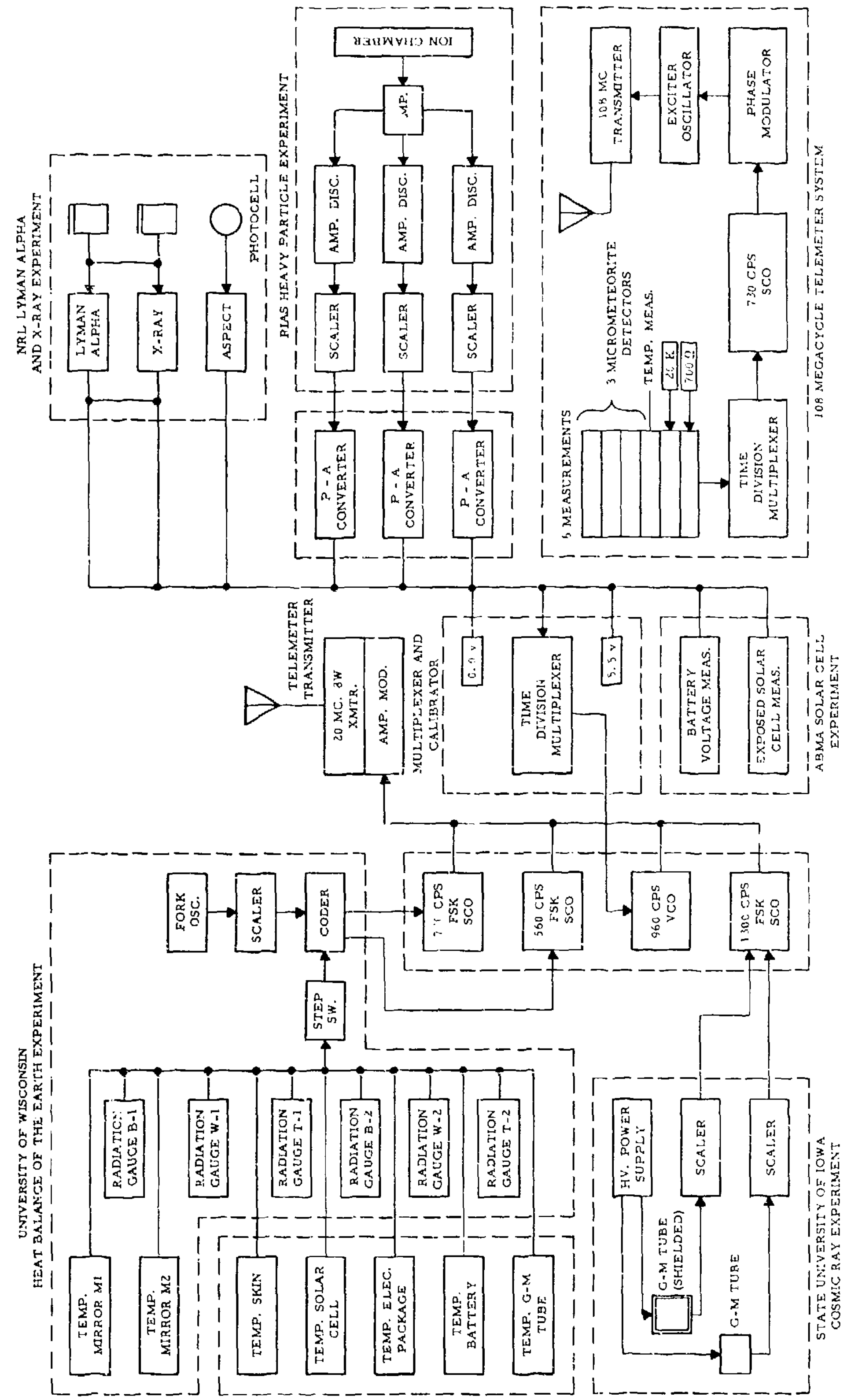
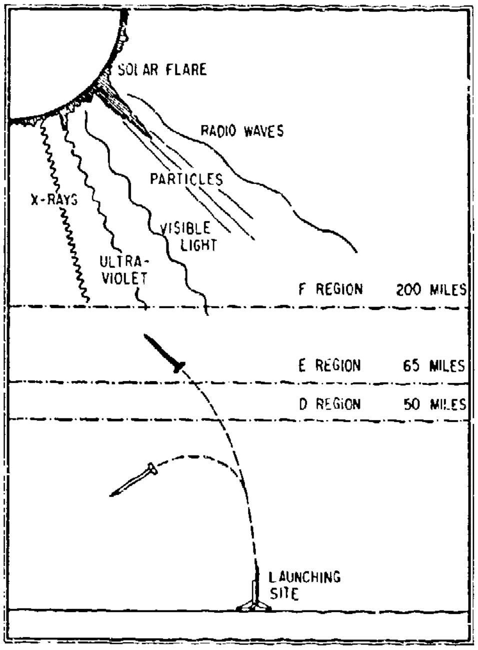
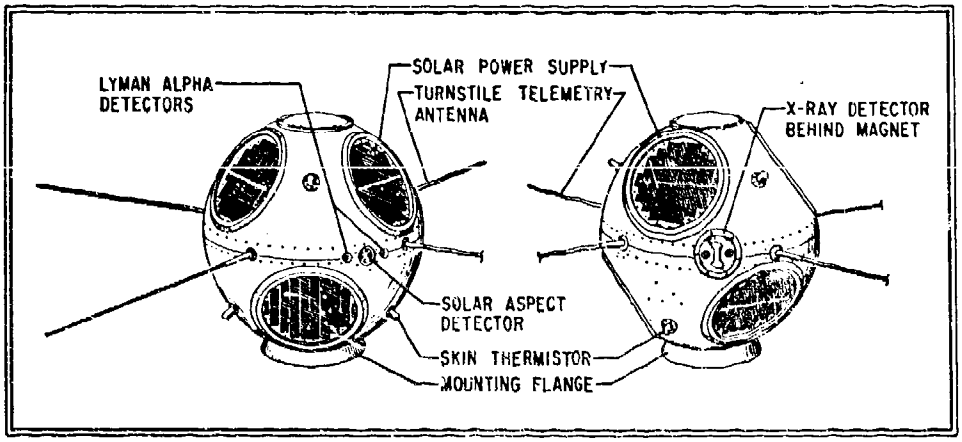


Fig. 3-18 Block Diagram of 1959 Iota Satellite (Explorer VII) Instrumentation



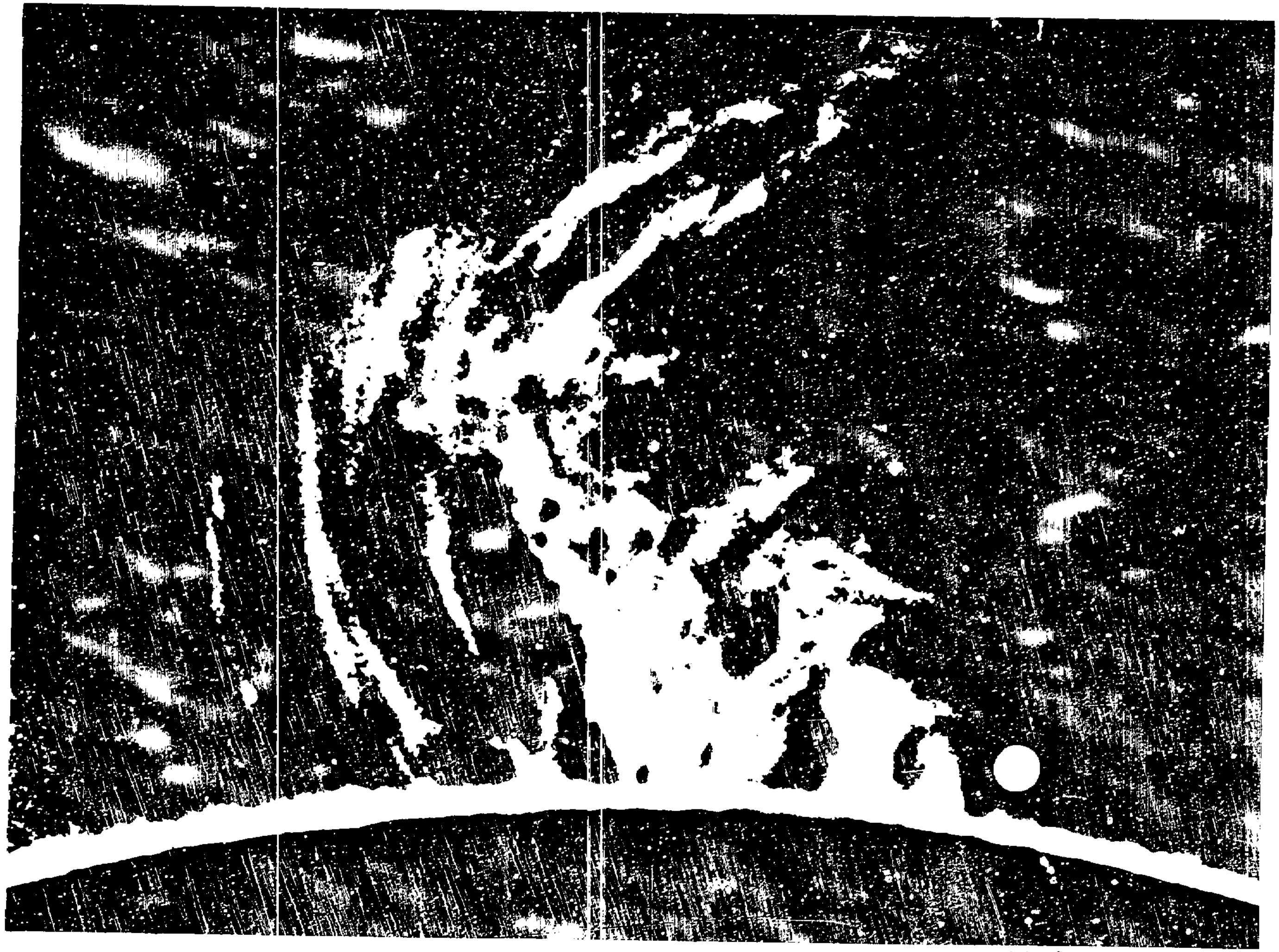
The Sunflare Experiment. The two-stage experimental rocket is launched immediately after a flare is reported, penetrating the ionospheric layers and measuring the flare radiations. Comparative wavelengths of the radiation spectrum are suggested schematically.

Figure 3-19



Two Views of 1960 Eta 2. (Adapted from NRL photographs.)

Figure 3-20



NASA PHOTO NO.
62-OSO-1

Fig.3-21 *Prominences beyond the limits of the sun's surface, taken by spectroheliokinematograph (motion pictures of the sun in monochromatic light).*

At the time of solar eclipse, these prominences appear as rosy-red protuberances at the limit of the sun. They may last several hours or longer. They are as extensive in size as the sun itself. The white dot at right, near the sun's surface, superimposed on the photograph, represents the earth, to scale. (Photo courtesy of Mount Wilson - Palomar Observatories, California Institute of Technology, and the National Science Foundation.)

Under exposure to the full ultraviolet spectrum of sunlight, there would be a progressive deterioration of the efficiency of the detectors as the result of photochemical decomposition of the nitric oxide gas. To minimize this effect, each tube is covered with a mask containing an aperature having an area of only 9.4×10^{-5} (about 1/10,000) cm^2. The response through this tiny aperature is sufficient to provide a readily measured current signal when the tube is exposed to the sun. The use of two tubes, mounted side by side and connected in parallel, provides backup in the event of failure of one of the tubes.

The Lyman-alpha ionization chamber will be used in a scanning telescope aboard Ranger 1 and 2 spacecraft (Ref. 271). The principal purpose of this telescope is to obtain a series of low resolution pictures of the earth and its exosphere in ultraviolet light near the Lyman-alpha wavelength (1216 Angstroms).

(c) Infrared Measurements and Devices

On June 24, 1959, an Aerobee-Hi research rocket carried aloft three spectro-radiometers, successfully demonstrating the feasibility of packaging precision infrared equipment for extreme environments and very limited space and power requirements.

In infrared spectroscopy, inadequate sensitivity often makes it difficult to obtain data on weak sources of radiation. To overcome this, Block Associates, Inc., with partial sponsorship of the Geophysics Research Directorate of the Air Force Cambridge Research Laboratories, has developed a technique of interference spectroscopy and reduced it to practical laboratory and field instruments. The interferometer spectrometer basically attains increased sensitivity by making more efficient use of the measuring time, by examining all wavelengths simultaneously, and by requiring no entrance slit, as in conventional instruments.

Since most detectors are not fast enough to follow the fluctuations of the radiation, the interferometer is used to "slow down" the waves.

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271 Scientific Experiments for Ranger 1 and 2, Jet Propulsion Laboratory, Technical Report No. 32-55, January 3, 1961, pp. 20-22

A block diagram of the spectrometer is shown in the accompanying figure.

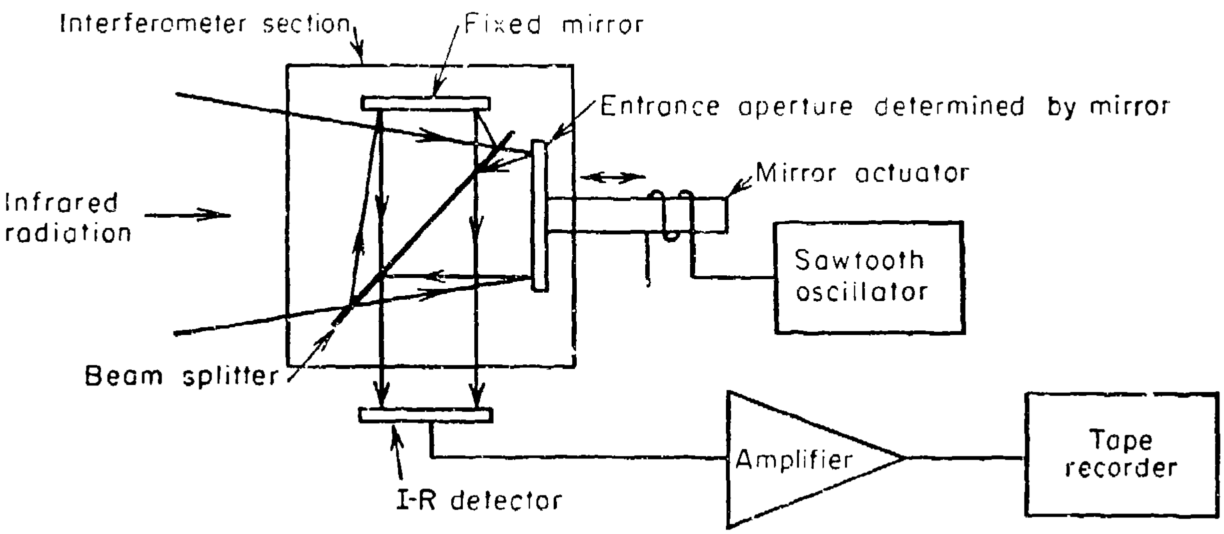

Figure 3-22 Interferometer Spectrometer

When one of the mirrors in the interferometer is moved back and forth at a slow constant velocity, there is an alternate brightening and darkening of the central fringe. The infrared detector is placed at the central fringe so that it converts the alternate brightening and darkening into an alternating electrical signal.

If the mirror velocity is kept constant, the frequency of the detector output is directly related to the wavelength of the incident radiation, assuming for the moment that the radiation is at one given wavelength. If another wavelength twice as long as the first should be substituted as the radiation source, the a-c output signal would be one-half the frequency of the first. The amplitudes of the two signal wculd remain the same if the maximum brightness of the two sources were the same. If incident radiation containing many wavelengths is introduced into the system, the output of the detector consists of a superposition of all the a-c signals which correspond to all the wavelengths in the source. This output is amplified and recorded on a magnetic tape which can be "played back" on a spectrum analyzer.

The Aerobee-Hi research rocket instrumentation consists of one filter radiometer using a lead sulfide detector, one filter radiometer using a flake thermistor detector, and one scanning spectrometer using a lithium fluoride prism and lead selenide detector. The total volume occupied by these instruments, including their battery power supply, was less than 300 cubic inches (about the size of a large loaf of bread): and the total power was less than 35 watts.

The satisfactory operation of the equipment and collection of radiation data throughout the rocket flight was climaxed by the recovery of the instrument packages after a "free-fall" from 120 miles altitude. All three instruments were recovered in sufficiently good condition to be flown again.

Figure 3-23 depicts an infrared horizon sensor developed by Barnes Engineering Company of Stamford, Connecticut for use in the Mercury Manned Spacecraft.

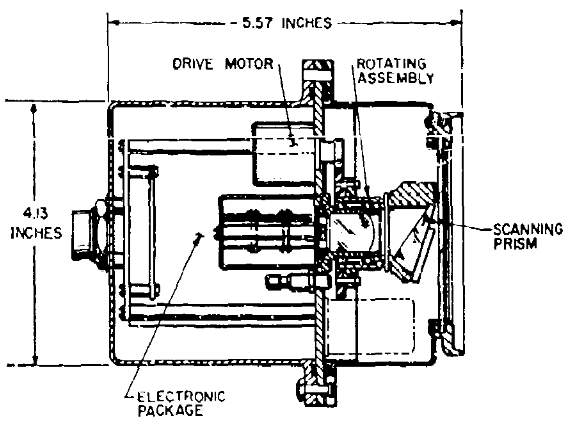

Figure 3-23 Infrared Horizon Sensor

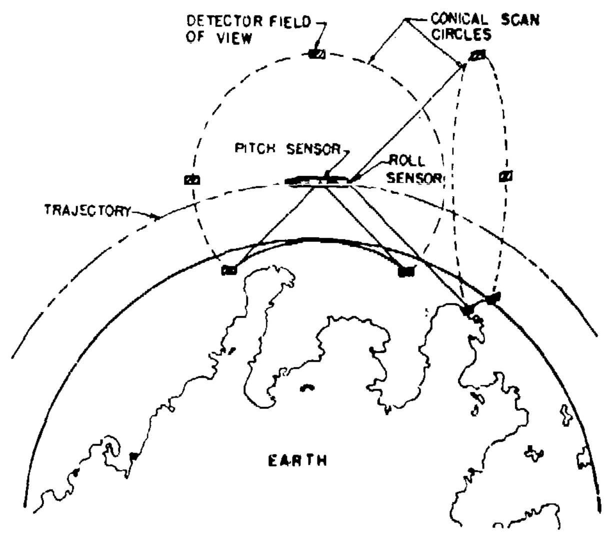

Figure 3-24 Horizon Sensor Operation

The astronaut makes observations through a periscope pointed downward at the earth. A means for keeping the spacecraft horizontal with respect to the earth is required to insure proper observation as well as planned performance by the astronaut of his other duties.

Two infrared horizon sensors are positioned at right angles to each other in the spacecraft;(see Fig. 3-24) one for sensing pitch errors, the

other for roll errors. These sensors continuously scan earth and space to detect the "thermal horizon" between the nearly absolute zero of outer space and the warmth of the earth's troposphere. This horizon is the best available stable reference for establishing a vertical to the earth below, affording accuracies of better than $\pm 1°$ from the true local vertical. Using this reference, the sensors generate electrical signals which are used to periodically correct the inertial platform which is the primary stabilizing element in the Mercury Spacecraft. Each sensor contains a detector for converting received infrared radiation to an electrical signal, a rotating prism for scanning the detector across earth and space, and a transistorized electronics system for processing the detector's electrical output signal and converting it to the form of pitch and roll correcting signals, in a package 5 1/2 inches long x 5 1/2 inches diameter, including mounting flange.

The accuracy with which the earth's infrared horizon can be determined is affected adversely by reflected solar radiation, which could produce disturbing discontinuities from cloud edges, topographical features, or the night/day division line.

Fortunately, spectral filtering will separate reflected solar radiation from the earth's self-emission. Solar radiation has a color temperature of about 6000 K, and appears almost entirely in the spectral-region from 0.2 to 2 microns. The earth, at a much lower temperature, radiates in the long wavelengths, and a thermal detector with high sensitivity to long wavelengths, a system can be made almost completely independent of solar radiation. A suitable combination is a germanium filter with a thermistor detector. Germanium is completely opaque below 1.8 microns, and

transmits reasonably well between 1.8 and 20 microns. Fig. 3-25 illustrates the spectral distribution of radiation received from the earth from a point in space and (dotted line) the transmission characteristics of germanium.

The horizon sensor will occasionally scan the sun. Precautions must therefore be taken so that this condition will not generate false data or possibly damage the detector with too long a period of concentration solar energy. In the Project Mercury capsule the sensor operates only for short periods at regular intervals, so a sun shutter operated by a centrifugal force was incorporated. Thus, the shutter opens only when the scanner is rotating and is not damaged by brief scanned exposure times. Fig. 3-26 is a block diagram showing electronics and function circuits.

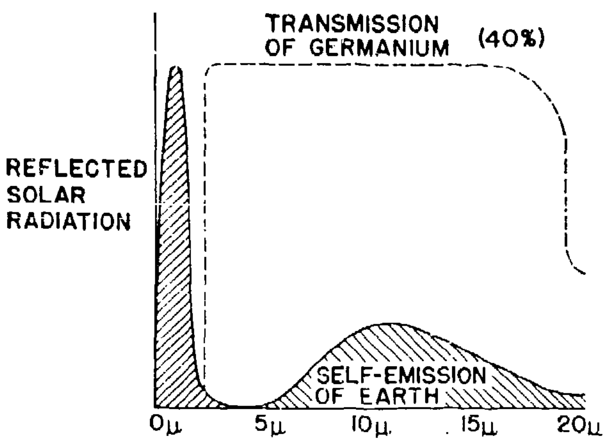

Figure 3-25 Spectral Distribution of Radiation Received from the Earth

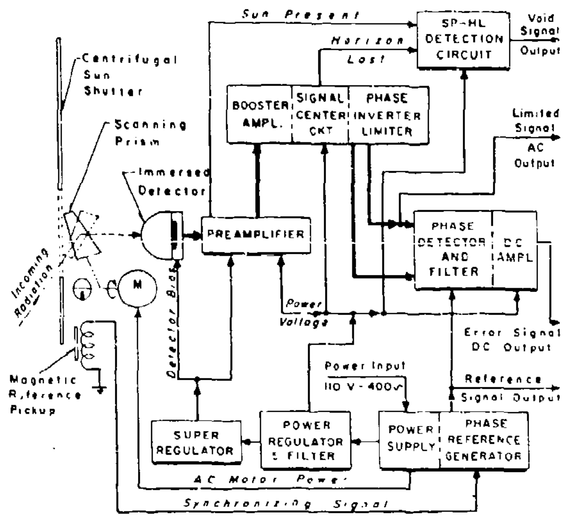

Figure 3-26 Horizon Sensor Block Diagram

The 1959 Alpha (Vanguard II) satellite included a cloud cover experiment (Ref. 272) developed by the U. S. Army Signal Research and Development Laboratory. The instrumentation used two photocells, each at the focus of one of two optical telescopes aimed in diametrically opposite direction at an angle of 45° from the spin axis of the satellite. As the sateliite

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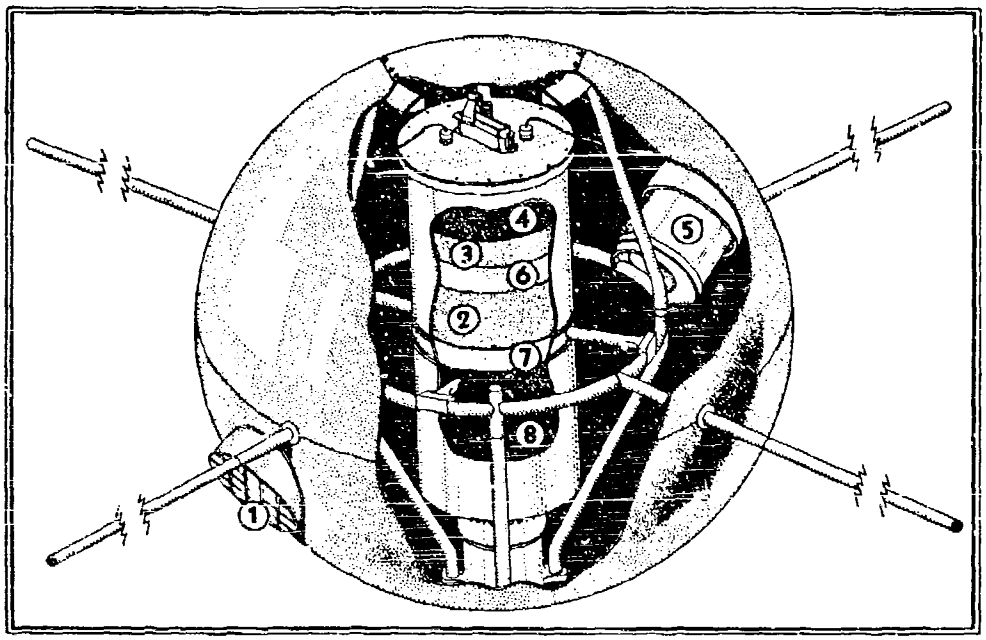
272 Fifth US-IGY Satellite, IGY Bulletin, Number 22, April 1959

circled the earth, the photocells measured the varying intensities of sunlight reflected from clouds (about 80%), land masses (15-20%), and sea areas (5%). The satellite's spin, about 50 rpm, caused the photocells to scan the earth in successive lines, producing a lined picture not unlike a television picture.

The measured reflection intensities were converted into electrical signals, which were stored in a type recorder within the instrument package. Separate solar batteries turned on the recorder only when the earth beneath the satellite was in daylight, giving 50 min of data per orbit. The 75-ft loop of recording tape accommodated all scanning data from the sunlit part of a single orbit. Once in each orbit, a selected ground station interrogated the satellite by signalling a command receiver within the satellite, causing the entire tape to be played back in 60 sec. The tape was then "erased" and the system triggered to begin recording again. At the interrogating ground station, the data were received on a wide-band magnetic tape recorder and the tape was immediately air-mailed to the US Army Signal Research and Development Laboratory for analysis and conversion into cloud-cover pictures.



Cutaway Diagram of Satellite 1959 Alpha. The instrumentation consists of (1) photocell light shields, (2) recorder, (3) interrogation radio receiver, (4) meteorological data transmitter, (5) photocell, (6) data electronic equipment, (7) tracking transmitter, and (8) mercury-cell batteries. From US Army photograph.

Figure 3-27

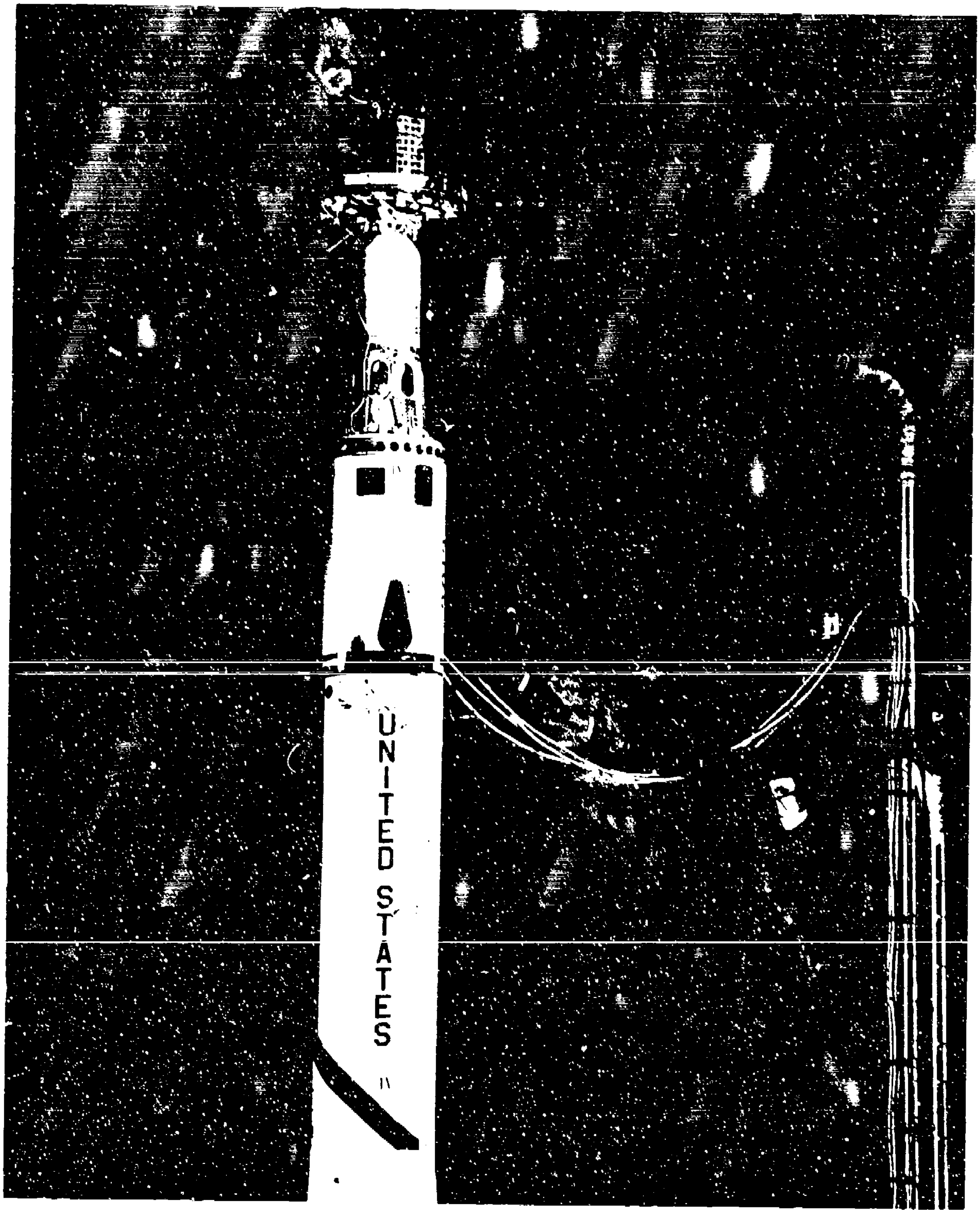


Fig. 3-28 Tiros II Mock Count Down and Tower Removal

The Tiros I weather satellite launched April 1, 1960 (Ref. 273) sent back over 20,000 usable TV pictures of the earth and its cloud cover. Functionally, Tiros I consisted of two separate nearly identical systems differing only in the type of lenses (wide-angle and narrow-angle) of the TV cameras used. Each system consisted of a television camera, a magnetic tape recorder, a TV transmitter, suitable command circuitry and a beacon for tracking purposes. A battery and solar cell charging system was used for power. The complete instrumentation system was quite complex to track the satellite, initiate a telemetry switching cycle to sample battery voltages and other operational characteristics, then command play back of recorded tape, select desired sequence of wide angle and narrow angle picture taking. The pictures were coded with orbit, altitude and sun-angle information. The TV picture was a 2 second frame time, 500 line scan requiring video bandwidth of 62.5 kc. See Fig. 3-30 for system component arrangement of Tiros I.

Tiros II, launched on November 23, 1960 continues the cloud cover experiment begun with Tiros I. (Ref. 274) Additional sensors were included to map solar and infrared, or heat, radiation in various spectral bands. One of the radiation experiments consisted of five radiation detectors, oriented at 45° to the spin axis, which scan through a combination of the satellite's rotation and its movement along the orbit. These detectors measure:

1. The earth's albedo--the percentage of reflectivity of radiant energy, or light--in the spectral range 0.2-5 microns.

2. Infrared radiation emitted by the earth and atmosphere combined in the range 7-30+ microns.

3. Emitted infrared radiation coming through the atmospheric "window" (the portion of the electromagnetic spectrum to which the atmosphere is quite "transparent") in the range 8-12 microns. Measurement in this spectral range should supply information that may permit (a) cloud detection, especially at night and over areas where the TV cameras are not operated; (b) determination of cloud-top temperatures and, accordingly, a rough measure of cloud-top height; and (c) determination of surface temperatures over cloud-free areas.

4. Radiation from the water-vapor spectral band, 6.3 microns ± 5%. These measurements should show the geographic distribution of the approximate upper margin of water vapor in the atmosphere, which, in some places, may be near the height of the tropopause (about 20,000-50,000 feet about sea level).

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273 Mesner, M. H., "Signal Processing In Tiros I Instrumentation System" IRE Transactions, Fifth National Symposium, 1960 on Space Electronics and Telemetry.

274 "The Tiros II Cloud-Cover and Infrared Satellite", IGY Bulletin, No. 43, January 1961.

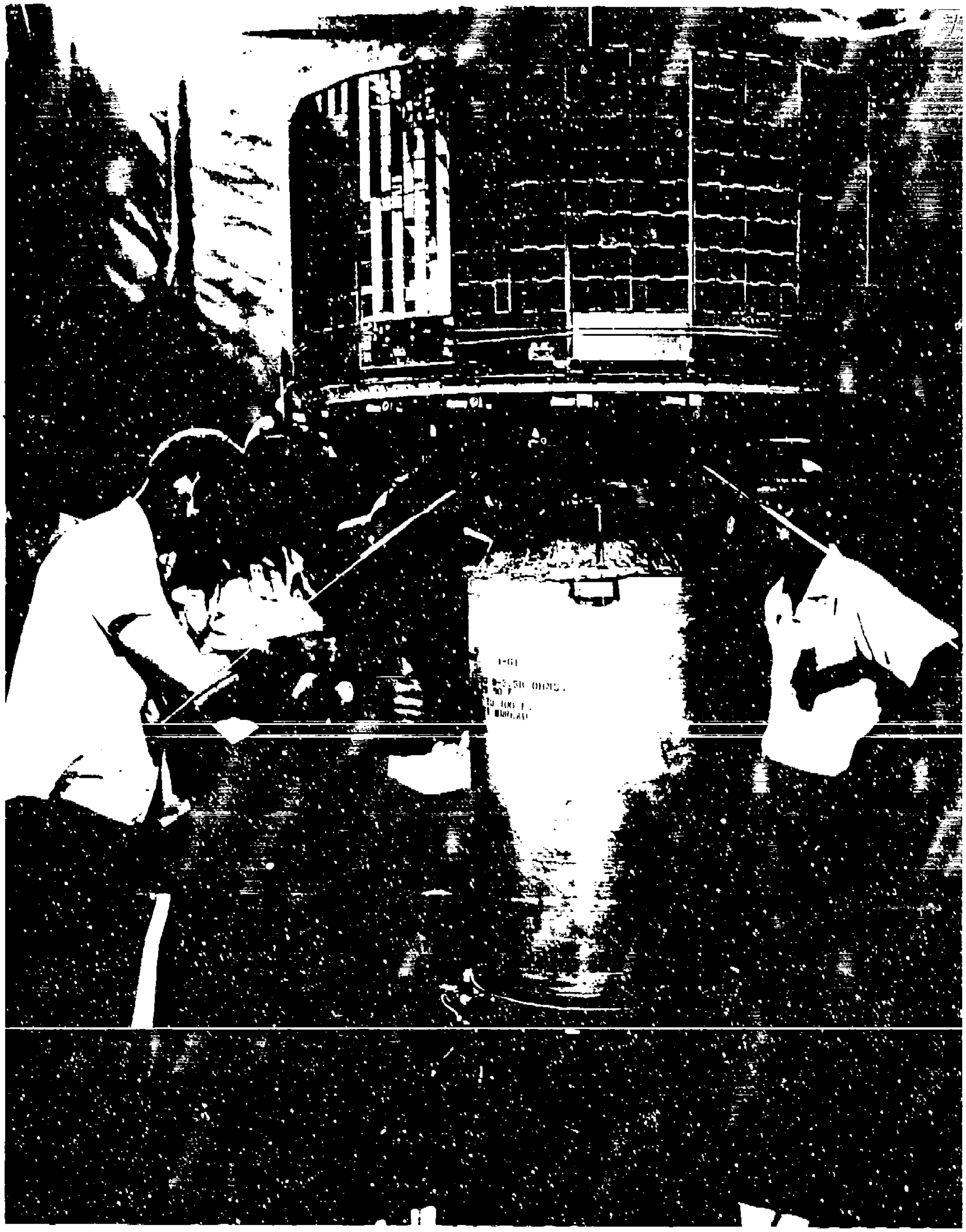

Fig. 3-29 Launch Preparations on Tiros III at Cape Canaveral. Launched at 5:25 a.m., July 12, 1961

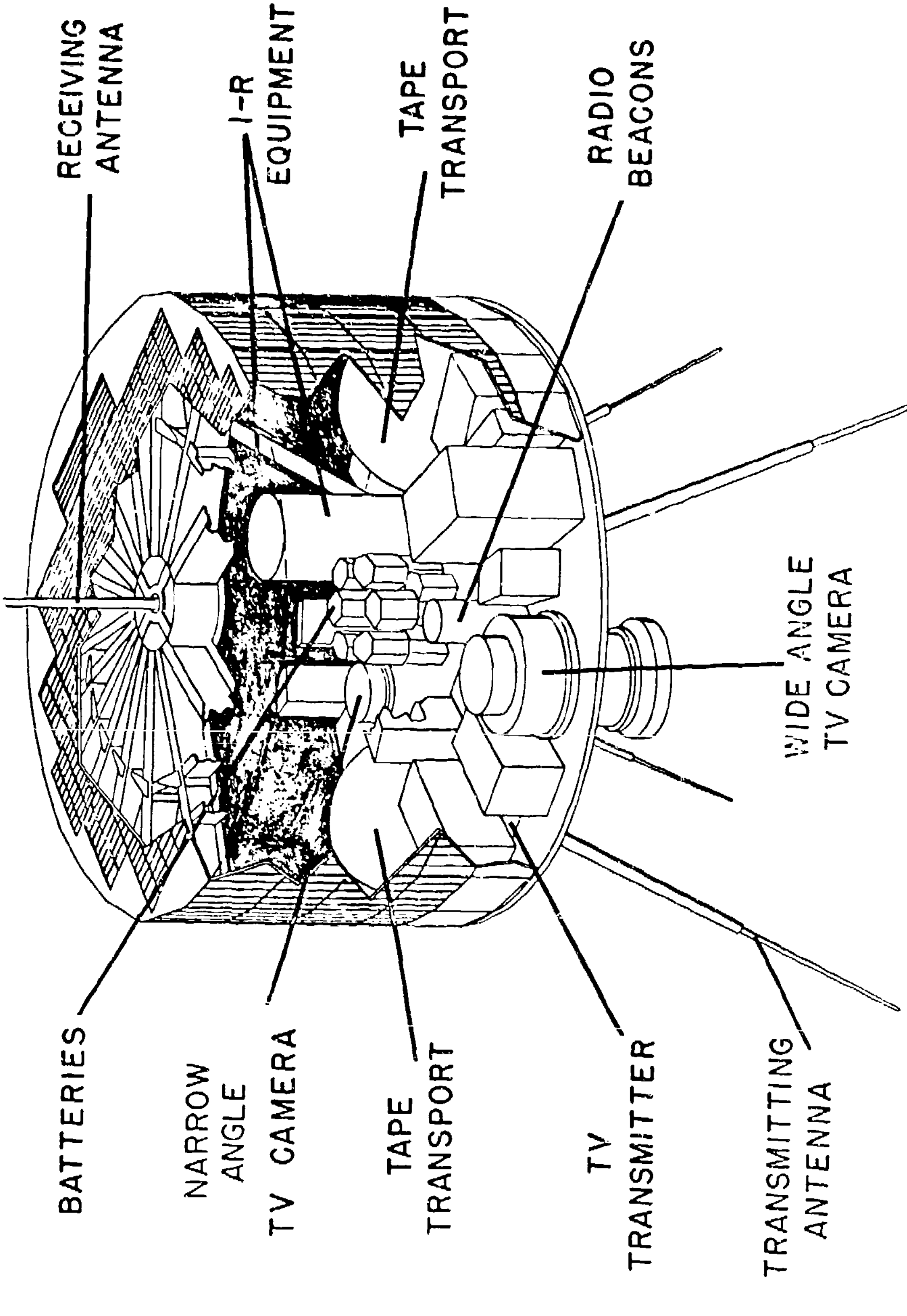

Fig. 3-30 System Component Arrangement of Tiros I

5. Visible radiation in the spectral range 0.5-0.7 microns. This visual channel intended to provide maps of visible radiation for use in relating the television pictures and the nonvisible-radiation maps.

The second radiation experiment consists of two sensors, one white and the other black, which together measure the heat balance of the portions of the earth's surface and atmosphere viewed by the wide-angle television camera. The white sensor measures heat radiation from the earth while the black sensor measures both visible (reflected solar radiation) and heat radiation.

(4) Nuclear and Penetrating Radiation Measurements

(a) X-Ray Measurements

Solar ultraviolet and X-ray radiations are responsible for the formation of the earth's ionosphere. They are variable and produce day-to-day and seasonal changes in ion density. During solar flares, these radiations cause sudden ionosphere disturbances which seriously disrupt long-range radio communication and navigation systems. Collection of data on these radiations may enable improvements in predicting the range of short-wave communications. Satellites have been instrumented for the purpose of measuring X-ray intensities and variations.

An experiment to measure X-radiation from the sun and its effect on the earth's atmosphere was included in the 1959 Eta earth satellite (Ref. 275). The main components of the experimental equipment were two identical ionization chambers which were sensitive to wavelengths of 1-10 Angstroms (X-rays in this range are produced in solar flares.) The ionization chambers were oriented about 120° apart on the satellite's equatorial plane and the maximum signal occurred when an ionization chamber "looked" in the direction of the sun.

The 1959 Eta X-ray instrumentation equipment also included an electrometer circuit and a peak-reading memory device. Currents generated in the ionization chambers were amplified by the electrometer circuit and the memory device retained the maximum Z-ray signal received during orbit. The memory core was the controlling element in an audio oscillator which modulated the satellite's telemetry transmitter upon interrogation by a ground station. Analysis of the modulation provides information on the intensity variations and energies of X-rays entering the ionization chambers.

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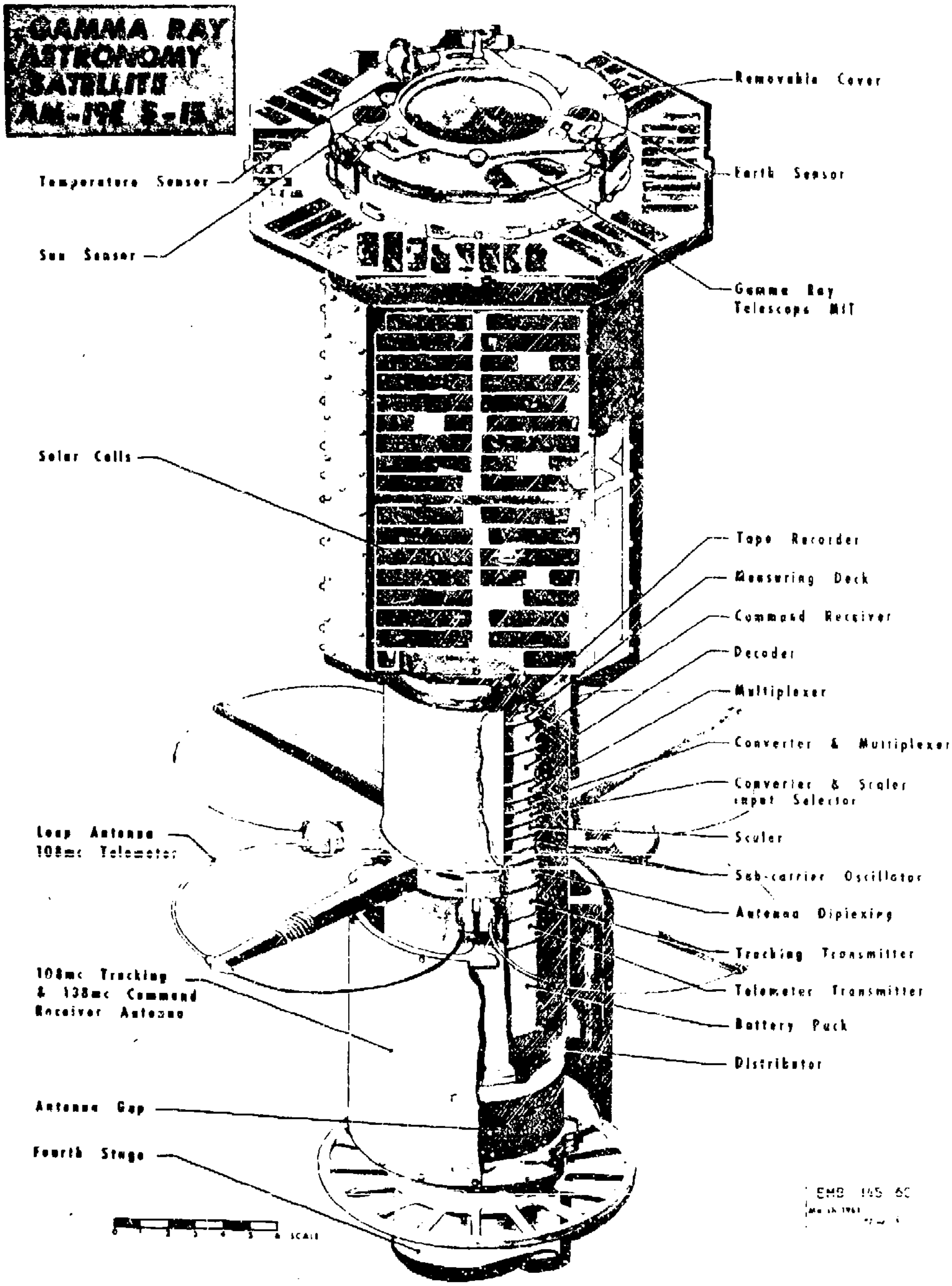
275 Same as Reference 263 op. cit. p. 12



NASA PHOTO NO.
61-JUNO IIB-1

Fig. 3-31 This is a cutaway drawing of the gamma ray astronomy satellite (S-15). A project of the National Aeronautics and Space Administration, the highly-sophisticated S-15 is designed to detect and measure high energy gamma rays emitted by the sun, stars and galaxies. It will be man's first attempt to measure these very high energy rays from sources other than the earth.

The 1959 Iota carried X-ray ionization chambers with beryllium windows and filled with argon gas (Ref. 276). These detectors were sensitive to wavelengths of 3 to 15 Angstroms.

An X-ray ionization chamber was used on the 1960 Eta 2 satellite. It contained a beryllium window with a surface density of 0.025 gm/cm^2 and an open area of 2.33 cm^2 (Ref. 277). The absorbing gas was argon at a pressure of 760 mm Hg. Maximum efficiency of the detector was 76% and occurred at 2.8 Angstroms. The X-ray chamber was mounted on the equator of the satellite behind the gap of a permanent magnet having a field strength of about 3000 gauss. The magnet served as a "broom" to prevent the passage of low-energy electrons of the Van Allen radiation belt. This was nearly 100% effective for energies below 0.5 mev.

(b) Plasma Probe (Ref. 278)

The plasma experiment of Explorer X was to obtain measurement of very-low-energy protons coming to the earth from the sun, and determine their direction of flow. An instrument weighting about 2.5 pounds was designed to measure the density, direction and bulk velocity of interplanetary plasma. Positive and negative particles would enter the probe through a six-inch circular aperature and pass through a series of grids behind which there was a collector. With this arrangement the probe was sensitive only to protons with velocities ranging from 6 mi/sec to 1000 mi/sec. Experiment was highly successful with 60 hours of data being received.

(c) Cosmic Radiation

Cosmic rays are electrically charged particles which bombard the earth continuously and from every direction. Being markedly influenced by the earth's magnetic field, low energy particles are deflected toward the vicinity of the two geomagnetic poles, and only the more energetic ones penetrate at the middle latitudes. Geiger counters and ionization chambers may be used for measuring their intensity and fluctuations.

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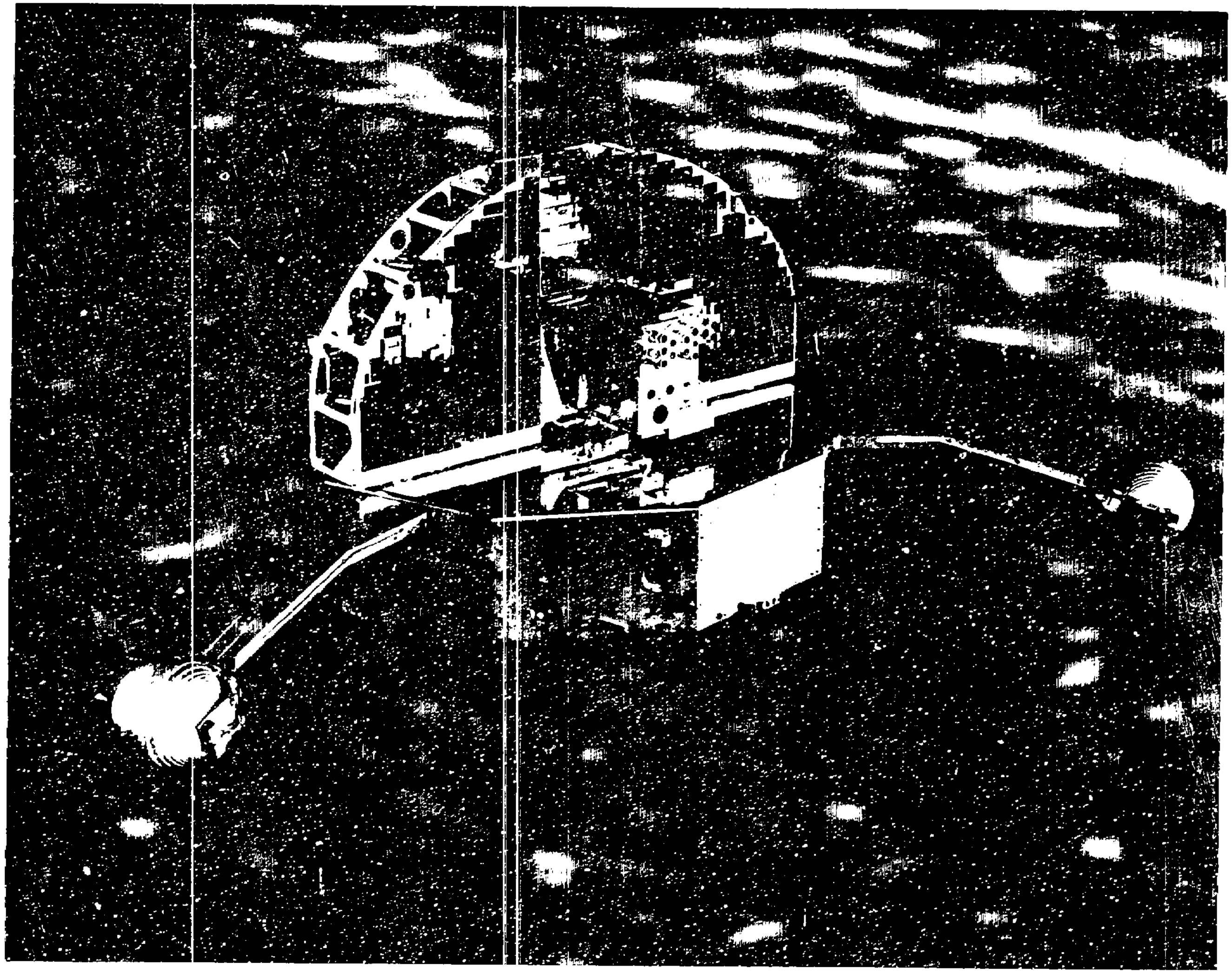
276 Same as Reference 268 op. cit. p. 13

277 Same as Reference 270 op. cit. p.3

278 "Explorer X Magnetic-Field and Plasma-Probe Satellite," IGY Bulletin, No. 48, June 1961.



NASA PHOTO NO.
62-OSO-6

Fig.3-32 View of 440 pound Orbiting Solar Observatory spacecraft which will attempt to measure ultra-violet, gamma and x-ray radiation's from the sun.

The National Aeronautics and Space Administration plans to launch the spacecraft from Cape Canaveral, Fla., within the next few days.

Ranger 1 and 2 spacecraft will carry a quartz-fiber integrating-type ionization chamber (Ref. 279). The chamber consists of a sperical volume of argon gas contained by a thin steel wall (See Fig.3-33). The entire working mechanism is made of fuzed quartz, which is an excellent electrical insulator. The areas shown in black in Figure 3-33 are covered with a conducting coat of aquadag. When no voltage is applied, the fiber, which has a conducting coat, lies about 0.020 inch from the collector. When the power is connected, the fiber is bent by electrostatic attraction and touches the collector, charging it to the battery potential. The fiber then moves back to its rest position away from the collector since the fiber, collector, and shield can are all at the same potential.

The electric field between the collector and outer shell is more than sufficient to collect all ions formed in the argon. The ionization current discharges the collector until the fiber again touches and recharges it, simultaneously producing a voltage pulse across a load resistor. Hence, the time between pulses varies inversely with the rate of ionization in the argon; a pulse occurs after about 10^{-10} coulombs have been collected from the argon.

The 1960 Alpha (Pioneer V) carried instrumentation to measure the intensity of high-energy radiation between the orbits of Earth and Venus, (Ref. 280). The University of Chicago developed instrumentation, a triple-coincidence proportional-counter arrangement, consisting of a bundle of argon-filled cylinders, six of them arranged around the seventh. The entire bundle, including a thin lead shield to screen out the lower-energy particles, is two inches square. Particles striking the counter ionize the gas in the tiny cylinders, causing electrical "blips" to be recorded as they penetrate one or more cylinders. The number of cylinders a particle can penetrate depends on its energy and direction.

(5) Other Ionization Measurements

The ionosphere probe 1960 Xi carried a single-grid ion trap and a multiple-grid ion trap to sutdy ionization in immediate vicinity of vehicle including ion sheath effects in areas surrounding the vehicle (Ref. 281). The ionosphere provides a near vacuum and ionization source and it is only necessary to provide a grid and plate or collector to complete a space vacuum tube.

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279 Same as Reference 271 op. cit. pp. 8-11.

280 Same as Reference 261.

281 Same as Reference 282.

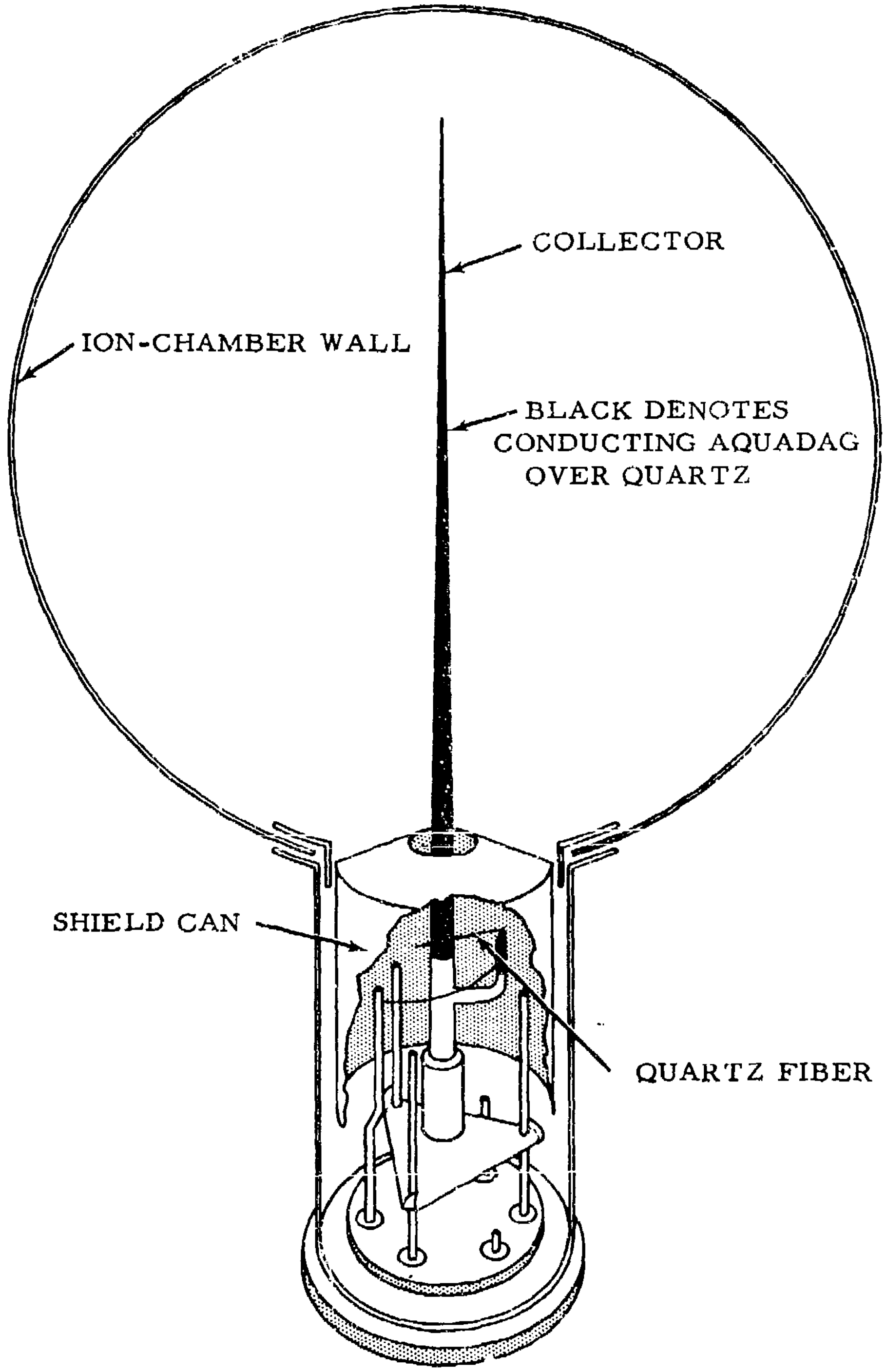

Fig. 3-33 Cross Section of Ion Chamber and Quartz Integrating System

The wide variety of experiments necessary when venturing into unknown regions can be illustrated by a list of the ranger 1 & 2 experiments plan. (Ref. 282).

1. Solar Plasma	- Solar Corpuscular Detector	- 6 detectors, 33 lb. total, 2.74 w pwr.
2. Solar Plasma/ Cosmic Radiation	- Semiconductor Detectors & Thin-Wall Geiger Counters a. CdS Photoconductor b. Thin-Wall Geiger c. Med.-Wall Geiger d. Au-Si Counter	- 6 detectors, 3.8 lb. total, 0.16 w pwr.
3. Cosmic Radiation	- Ionization Chamber	- 1.2 lb., 4 mw pwr.
4. Cosmic Radiation	- Triple-Coincidence Telescopes	- 9 lb. total, 0.5 w pwr.
5. Magnetic Field	- Rubidium Vapor Magnetometer	- 5.75 lb., 4.1 w pwr.
6. Neutral Hydrogen	- Lyman Alpha Telescope	- 15 lb., 1.4 w pwr.
7. Cosmic Dust	- Micrometeorite Composite Detectors	- 3 x 6 x 5 1/2 inches, 3.55 lb., 0.2 w pwr.

Brief descriptions of assorted instrumentation included in the "Able" series (Pioneer I, II, V, Explorer VI and others) may be found in Ref. 283 and Ref. 284 discusses experiments in Explorer VII.

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282 Hibbs, A. R., Eimer, M., Neugebauer, M., "Early Ranger Experiments", Astronautics, September 1961.

283 Coleman, P. J. Jr., "Signal Processing For Space Vehicle Experiments", Fifth National Symposium on Space Electronics and Telemetry, 1960.

284 King, O. B., "Signal Processing in Explorer VII", Fifth National Symposium on Space Electronics and Telemetry, 1960.

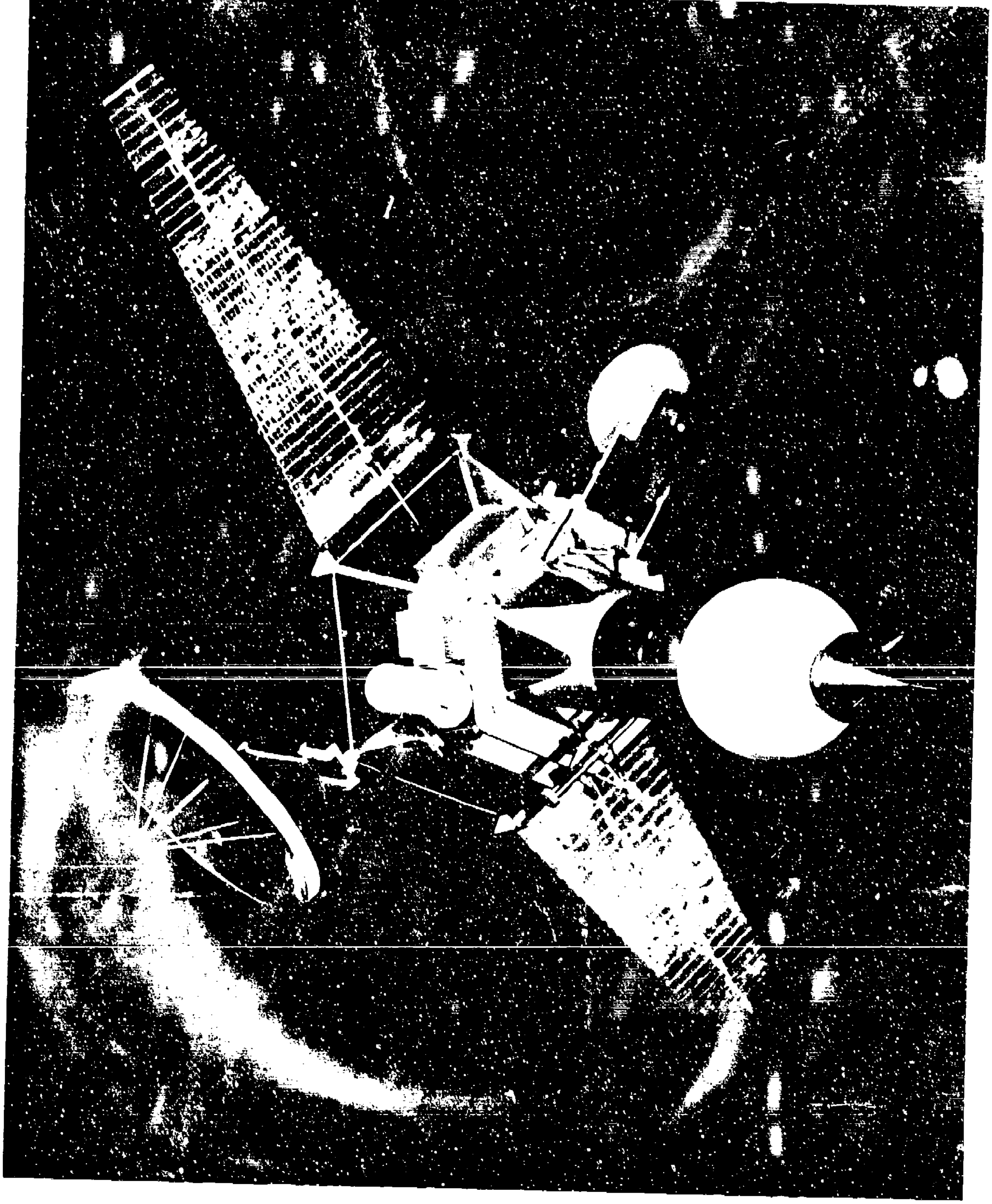

Fig. 3-34 Ranger III Payload

c. Project Mercury Aeromedical Data Display

A description of the aeromedical data display as part of the overall monitoring and control of a manned orbiting space capsule is presented (Ref. 285) illustrating application of bio-instrumentation in space vehicles.

The aeromedical position presents those quantities which are considered to be vital to the monitoring of the Astronaut's physical condition. The meter display is arranged so that the four primary measurements, Percent Oxygen Remaining - Main Supply, Body Temperature, Respiration Rate and Pulse Rate, are in a column at the left of the display. Ranged to the right of the Percent Oxygen meter are measurements relating to or having causative effects upon the Capsule atmospheric environment such as Percent Oxygen Remaining - Emergency Supply and Suit, Cabin, Partial Oxygen and Partial CO_2 pressures, respectively.

Likewise, to the right of the Body Temperature meter are found causative measurements such as Suit Inlet, Cabin and Inner Skin temperatures and Percent Coolant Quantity Remaining. The arrangement allows the monitor (in this case a medical man) to quickly scan the four most vital meters vertically and, should trouble be indicated on either the Percent Oxygen or Body Temperature meters, scan in a horizontal line to the right to locate the trouble source.

Immediately to the right of the Pulse Rate meter is the Cardioscope, which allows for EKG waveform examination. Included in the Cardioscope circuitry are provisions for aural monitoring of heartbeat, change of oscilloscope writing speed and selection of either of the two EKG waveforms for display.

The analog voltages to drive the Respiration Rate and Pulse Rate meters are derived from specially designed counting circuits. The Respiration Rate circuit counts respiratory cycles over a 30 second period, while the Pulse Rate circuit counts heartbeats over a 15 second period.

The rate-to-analog system for measuring pulse rate consists of dual decade counter circuits. One decade counter provides a continuous DC output for display on the DC meter for a 15 second period while the outer decades are counting the pulses for the next 15 second period.

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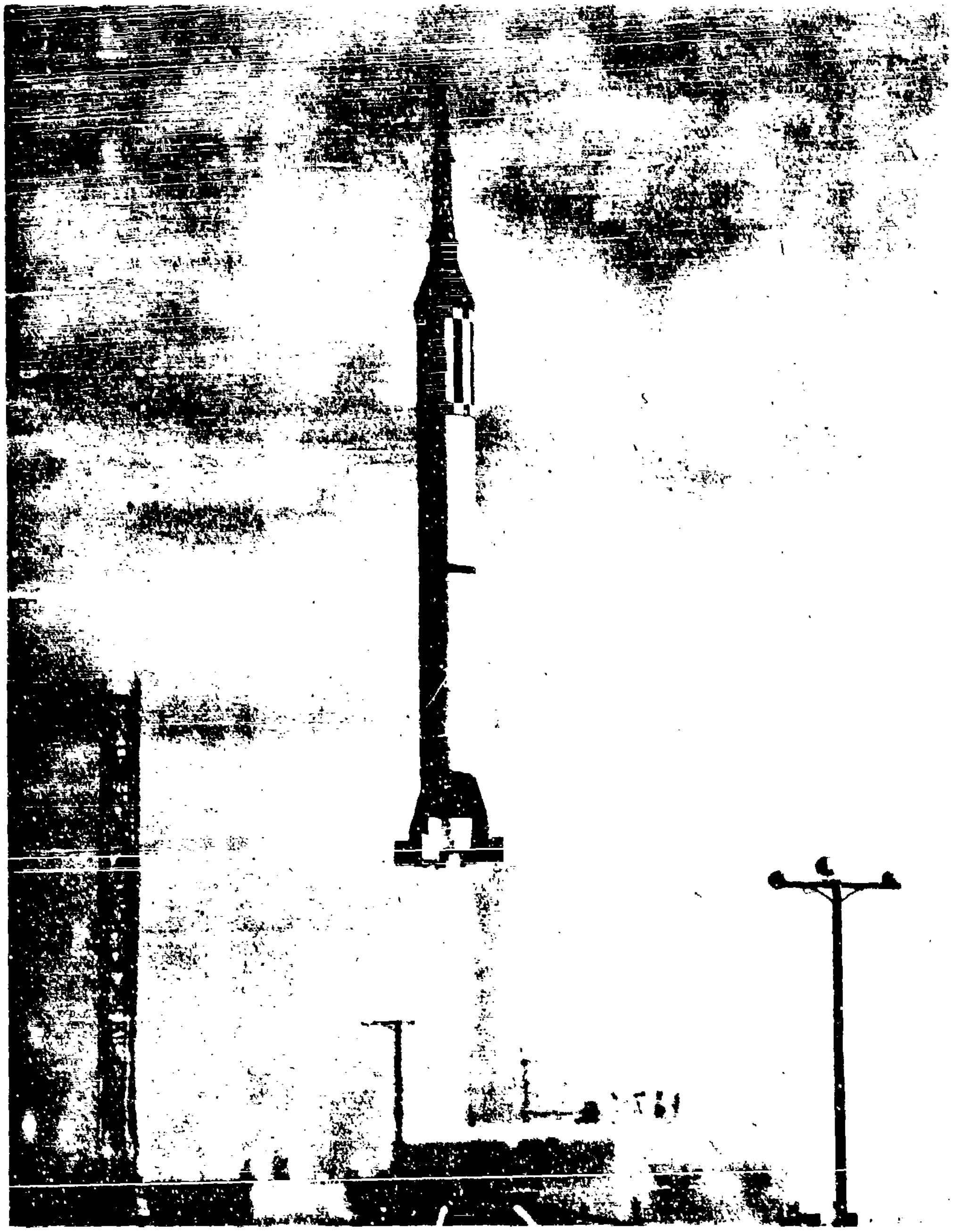
285 Ferber, D., "Project Mercury World-Wide Telemetry and Display System", Proceedings of National Telemetry Conference, 1960



NASA PHOTO NO.
61-MR4-80

Fig 3-35 CAPE CANAVERAL, FLA. -- A Project Mercury spacecraft carrying Astronaut Virgil I. "Gus" Grissom on the Nation's second manned space flight landed in the Atlantic Ocean about 305 statute miles from here and about 145 statute miles east northeast of the Grand Bahama Island at about 7:36 a.m., EST. today. The craft reached an altitude of about 118 statute miles and a speed of approximately 5,310 miles an hour.

The suborbital flight of the Mercury-Redstone 4 required about 16 minutes. Preliminary data indicate the pilot performed satisfactorily during flight.

The wave shaping circuit differentiates between the R wave, which is used to provide the count and the T wave, which may approach the amplitude of the R wave under certain conditions. Figure 3-36 shows a typical EKG waveform. The output pulse of the wave shaping circuit is fed to the trigger gate amplifier. The trigger gate amplifier in turn develops a pulse with a rise time of less than one microsecond, which is the requirement for driving the decade counters. Each of the counting units is comprised of two decades, representing pulses per minute in units and tens. The outputs of the units and tens decades, which are staircase voltages, are added across a resistor summing network in the ratio of 10 to 1. Another decade counter will count the 1 pps timing signals, developing an output for each 15 input pulses, thereby switching the trigger output from one counting circuit to the other and simultaneously from one switching network output to the other. The system for measuring respiration rate is similar to that for heartbeat except that a decade counter is employed which develops one output pulse for each 30 one second timing pulses.

In addition, the Aeromedical Observer has available immediately to his left, a direct writing, 8 channel pen recorder upon which EKG and respiration waveforms are available in a familiar form as well as recordings of derived pulse rate and respiration rate for the purpose of noting trends.

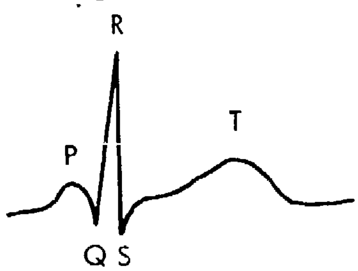
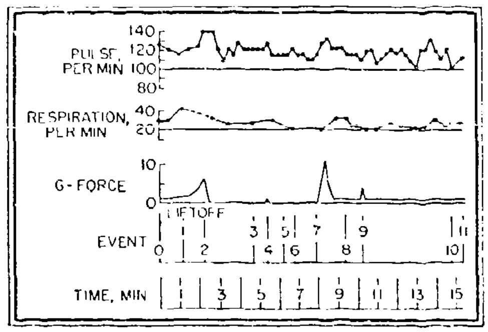


Figure 3-36

Typical EKG Waveform



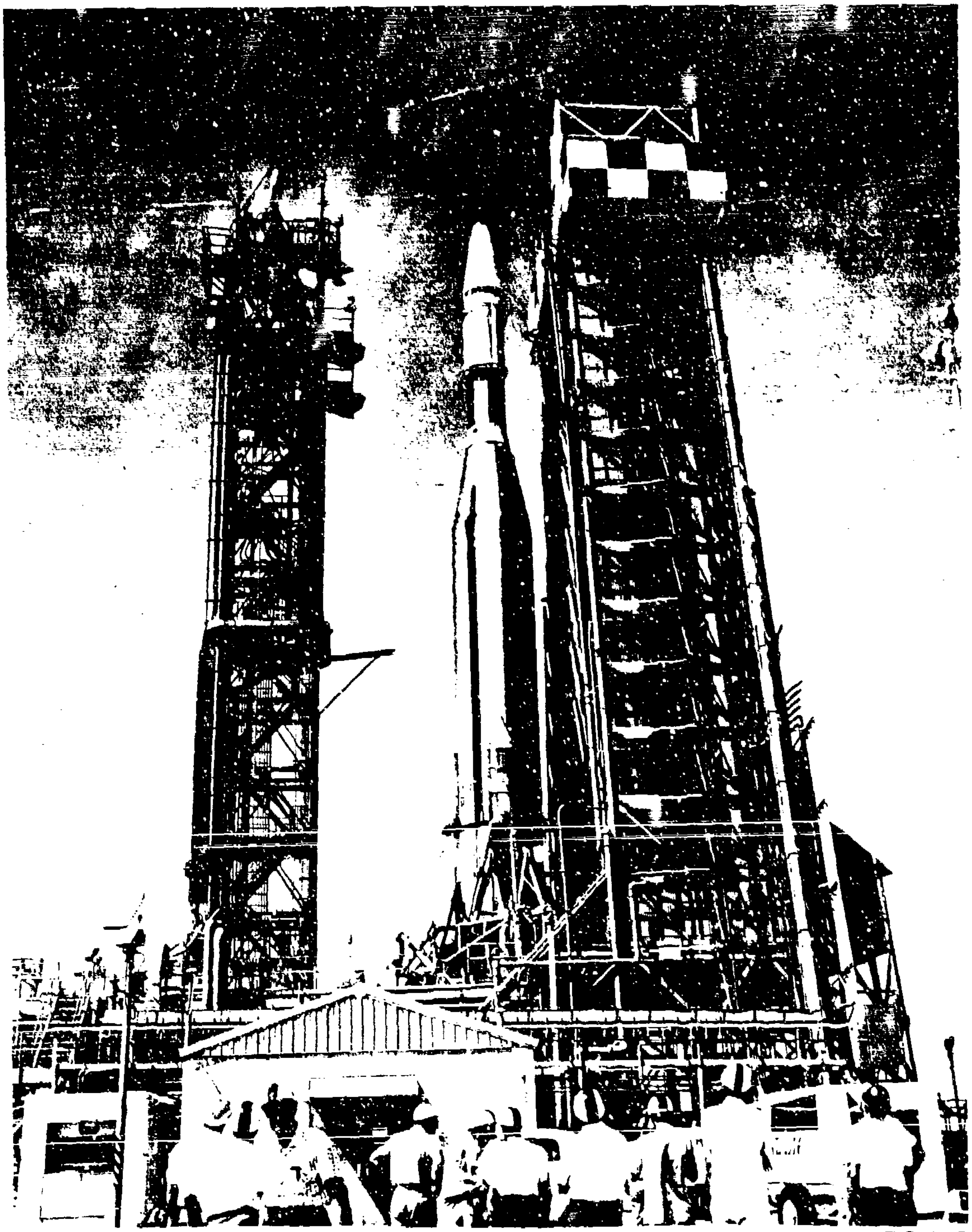
Astronaut's Pulse and Respiration Variations during MR-3 Flight. Flight time, G-force profile, and major flight events are shown for comparison. Events are as follows: (1) maximum dynamic pressure; (2) launch-vehicle engine cut-off, spacecraft-booster separation, and spacecraft turnaround; (3) orientation to retro-fire attitude; (4) retro-fire; (5) jettison of retro-package; (6) orientation to re-entry attitude; (7) .05 G, at beginning of re-entry into denser atmosphere; (8) opening of drogue parachute; (9) opening of main parachute; (10) impact with water; and (11) loss of telemetry signal. NASA diagram.

Figure 3-37

Measurements of Vital Physiological Elements of Astronaut Shepard Before and After MR-3 Flight

Vital Physiological Elements	Preflight −8 hr	Postflight	
		Shipboard	+3 hr
Body weight	169 lb 4 oz	167 lb 4 oz	166 lb 4 oz
Temperature, °F	99.0 (rectal)	100.2 (rectal)	98 (oral)
Pulse per min	68	100	76
Respiration per min	16		20
Blood pressure, mm Hg:			
Standing			102/74
Sitting	120/78	130/84	
Supine			100/76
Pulse per min:			
Before exercise	68		76
After exercise	100		112
Time for pulse to return to normal	2¾ min		3 min

Table 3-8



NASA PHOTO NO.
61-Ranger II-6

Fig.3-38 CAPE CANAVERAL, FLA. -- Atlas Agena B with the Ranger II payload stand ready on Pad 12 for launching. Ranger II same as Ranger I designed to study the nature and activity of cosmic rays, magnetic fields, and radiation and dust particles in space. The experiment will also seek to discover if the earth carries along with it a comet-like tail of hydrogen gas. Ranger II will be aimed at the moon, but will be sent off on a long trajectory into space reaching nore than a half million miles from earth. The round trip will take perhaps 50 days.

SECTION IV

TESTING AND CALIBRATION

4-1 INTRODUCTION

The material presented in this section has been compiled from information solicited from instrumentation groups and manufacturers of transducers and test equipment, and from reviewing a great number of technical reports and manufacturer's bulletins. An attempt was made through survey and solicitation letters to obtain from transducer users, general and specific evaluation and calibration techniques and procedures used at their organization. Apparently most of these procedures have not been documented or at least not in such form to be considered an operational or functional method. Much of the testing and calibration of instruments is done by highly skilled persons thoroughly trained in the use of their particular test equipment, and with much practical experience to evaluate observed data to determine results. Explanation and description of their techniques are not always applicable as basic methods, yielding step-by-step procedures.

Most of the detailed documentation has been tests of specific models of instruments to perform a specific task related to an over-all measurement or control effort. Tabulated data and results as to the instrument meeting manufacturer's specifications is usually presented. Analysis of test procedures rarely accompanies the data and results. Test procedures vary from one instrumentation group to another mainly because of different test equipment available. Good test equipment is expensive and for non-production use very versatile and is, therefore, used many times, long after better techniques become known. Many test groups specialize in limited phases of testing such as for just one environmental effect, or static tests only, or at the other extreme an over-all go/no-go comparison. It is difficult to correlate data from such individual groups to formulate general and over-all testing and calibration procedures.

A general survey questionnaire on telemetry transducers was sent to over 600 transducer manufacturers and transducer user organizations. Returns from over 100 of these groups indicated interest in submitting transducer calibration and test techniques. The survey was followed up with specific letters of solicitation indicating the type of material desired for inclusion in the handbook. Most of the returns from these letters (and there were only a few) were quite narrow in scope, usually sales bulletins. Some information has been edited

from this type material and reference made to other thought to be of interest to the handbook user.

There are many NBS reports documenting very well performance tests on particular instruments. They usually give a detailed description of the instrument tested, manufacturer's specifications, a brief description of test methods (or reference to a more detailed report on the use of a particular measurement device or standard) tabulated test data and performance characteristics. Table 4-1 is a list of NBS Reports pertaining to testing various transducers. (Ref. 286)

4-2 GENERAL

a. User Considerations (Ref. 287)

(1) Relation of Procurement to Laboratory Calibration

The procurement of transducers should be based on performance specifications which are commonly understood by the manufacturers, vendor and the end user. The user's laboratory calibration procedures should be similar to the methods used by the factory and the user would be wise to request written test procedures from the vendor as part of the procurement activity. Mutually acceptable test equipment and methods will assist to further define the intent of the detailed specification and to establish most of the causes for rejection of the transducer. The user should not expect that the specification will exactly fit all contingencies even though it may be rather concise and perhaps be of moderate length. The vendor's good will can frequently be relied upon to resolve the disposition of newly discovered undersirable characteristics.

Sample units should be obtained prior to a major procurement to provide evidence that the individual calibration data obtained by the user agrees favorably with the data furnished by the vendor. The user should receive a copy of the individual factory calibration data with each transducer. The user's initial laboratory calibration, which should also serve as a receiving inspection, should always agree with the vendor's data within a

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286 Pearlstein, Joseph, Bibliography of NBS Reports on Performance of Telemetry Transducers and Calibration Methods, Diamond Ordnance Fuze Laboratories, TR-887, 12 October 1960.

287 Bronson, R. D., "General Comments on Laboratory Calibration of Transducers, "Engineering Flight Test, Convair, A division of General Dynamics Corp., Fort Worth, Texas, January 13, 1961, (special contribution)

Table 4-1 Reports on Performance of Telemetry Transducers

NBS Report Number	Instrument Maker	Device	Model Number	Range	Principle
*1B112	Trans-Sonics	accelerometer	4-9	±5g	strain gage
1B113	Trans-Sonics	accelerometer	4-8	±2g	strain gage
1B118	Trans-Sonics	accelerometer	4-10	±10g	strain gage
*1B119	Trans-Sonics	accelerometer	4-11	±20g	strain gage
1B123	Bendix	inductance oscillator	TOL-5B		
1B130	Bendix	angular position pickup	TTO-1A	0 to 1100°	variable reluctance
*1B137	Sperry	pressure cell	653323-1020	0 to 115 psi	variable reluctance
1B140	Bendix	pressure cell	TTP-9A	0 to 50 psi	variable reluctance
*1B141	Sperry	pressure cell	653322-1019	-15 to +85 psi	variable reluctance
*1B143	Sperry	pressure cell	653322-1070	-14 to +15 psi	variable reluctance
3192	Gulton Mfg. Co.	accelerometer	A-403	0.1 to 600 g	piezoelectric
*3235	General Electric	accelerometer	VDA 122 C 759G-1	±50g	piezoelectric
3261	Consolidated	pressure cell	4-310	0 to 150 psig	strain gage
3480	Giannini	potentiometer	8517A-10-20	0 to 3600°	resistance
3490	Galetronics	potentiometer	LE-84	0 to 87 inches	resistance
3721	Bourns	pressure cell	702	0 to 100 psia	resistance
3914	Statham	accelerometer	A2G-15-450	±1.5 g	strain gage
4154	Consolidated	velocity pickup	4-118	50 to 500 cps up to 0-12/ 0-12"/sec or 0-100g	electromagnetic
4259	Wiancko	accelerometer	A9-1002	±5g	variable reluctance
4423	Statham	angular accelerometer	AA6-6-320	±6 rad/sec/sec	strain gage
4541	Decker Aviation	capacitance to volt. transducer	901-1	10 uuf to 100 uuf differential	ionization transducer
4776	Bourns	accelerometer	602A No. 1001 & 1331	±5g	resistance
4808	Statham	accelerometer	A17-50-335, 729, 730	±50g	strain gage
4973	Kistler	pressure trans.	SLN 370, 371	0 to 1500 psig	piezoelectric
5175	Genisco	accelerometer	GL032 No. 7762-63	±1g	strain gage

Table 4-1

NBS Report Number	Instrument Maker	Device	Model Number	Range	Principle
5315	Markite	potentiometer	Types 2234, 2094	1.750 in., 360°	resistance
5705	Datran	pressure transducer	P103, 6172, 73	0 to 50 psig	variable reluctance
6298	Fairchild	potentiometer	"FILMPOT" No. 771	360°	resistance
6299	IRC	pressure cell	"COMPUTRAN"	0 to 100 psig	resistance
6300	Genisco	accelerometer	GMO	±15g	resistance
6336	Norwood	pressure cell	EFK	0 to 1000 psig	bonded strain gage
6603	Donner	accelerometer	4310	±2g	servoed force bal.
6633	Humphrey	accelerometer	LA03-0304-1	±3g	resistance dashpot damping
6651	Solid State Elect.	pressure pickup with FM oscill.	"OSCIDUCER"	0 to 50 psig	variable inductance transistor oscill.
6942	Dynamic Inst. Co.	pressure cell	APT-61-50	0 to 50 psi	strain gage
7066	Columbia Research	accelerometer	302	.03 to 40000g	piezoelectric

6193 A Two-Inch Range Precision Mercury Manometer

6907 General Characteristics of Strain Gage Accelerometers Used in Telemetry

Reports on Calibration and Test Methods

3299 High-range accelerometer calibrations.

3339 Determination of sinusoidal acceleration at peak levels near that of gravity by the "chatter" method.

3924 Methods for steady-state accelerometer calibrations of to ±4000g and test results of two accelerometers, Model A314-T, manufactured by Gulton Manufacturing Co.

4222 A method of determining dynamic response of a pulse averaging FM discriminator.

4434 A torsional vibration calibrator.

4094a A simple, objective test for cable noise due to shock vibration or transient pressures.

4910 The shock tube as a facility for dynamic testing of pressure pickups.

5730 A dual centrifuge for generating low frequency sinusoidal accelerations.

realistic tolerance. After an independent repeat check, if the user's data still differs from the vendor's data by an unreasonable amount, the transducer should be returned to the vendor for recalibration or replacement. If the quantity warrants it, the ability of the transducer type to withstand certain extreme environments may best be judged by a more complete environmental test on a random sample of a group of identical type transducers.

(2) Relative Measurement Concept

Most of the data requirements of flight tests are satisfied with the measurement of a differential or relative change. Even many so-called "absolute" devices are used to measure a relative change and may ususally be laboratory calibrated using the concept of Sensitivity Slope. An example is the resistance-bridge pressure transducer which, although labeled "Absolute" and constructed with a 0 psia reference, is an instrument used as a relative measurement device. Since this transducer is subject to drift, an external balance is usually employed on the aircraft and the output is nulled at some known reference pressure; hence, the measurement technique assumes the relative concept. On the other hand, consider a potentiometer-output absolute pressure transducer. The output voltage ratio of such a unit may be used to represent specific (calibrated) input absolute pressures. In this case, the built-in transducer reference pressure is 0 psia. If the transducer is to be used without a new "reference" stated, then the laboratory calibration must give a reference intercept point as well as a sensitivity slope.

(3) Transduction Ratio

All true "transducers," that is those instruments that have a transduction ratio, should be calibrated and used with ratio techniques in mind. Examples of such transducers are those employing a resistance bridge, potentiometer or differential transformer. A resistance bridge is said to have a change in open circuit output of Q_1 millivolts per one volt input for a change of one unit stimulus input. The sensitivity of a potentiometer (voltage divider) output device is similarly stated as Q_2 millivolts per volt for a change of one unit stimulus input, and differential transformer output devices are said to have a sensitivity of Q_3 volts output per volt input per unit stimulus input.

(4) Self-Generating Transducers

Self-generating velocity-type vibration transducers may be calibrated by the ratio method against a reference pickup coil, commonly called the "Monitor" or "Signal Generator" coil, in the electrodynamic shaker-calibrator. The reference coil has a much higher output than the pickup under test and is established as a reference or "transducer standard" coil having a known output voltage per inch per second velocity. Thus, the pickup being calibrated deflects a vacuum tube voltmeter a certain amount and a portion of the reference standard coil output voltage can be made to cause the same voltmeter to deflect the same amount. The "portion" is read out on a calibrated attenuator.

Self-generating piezoelectric vibration transducers are usually calibrated on an electrodynamic calibrator shaker. The input acceleration amplitude may be determined from calibration curves by monitoring the frequency on an electronic counter and the shaker velocity (monitor coil) amplitude on a voltmeter. The output of the piezoelectric transducer is "read out" through its associated cathode follower or amplifier to a suitable voltmeter.

(5) Typical Static Considerations

A typical static calibration consists of tabular data giving the electrical output nominally for 11 static input points, representing every 10% of full range, in both increasing and decreasing steps. Thus, for a unilateral input transducer, the calibration is started and completed at the same full-range end-point after 21 data points are recorded. That is, output datum is obtained fro each input of 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 0% of full range. For a symmetrical bilateral transducer, the calibration commences at the 50% of full-range input point and output figures are obtained at 50, 40, 30, 20, 10, 0, 10, 20, 30, 40, 50, (50), 60, 70, 80, 90, 100, 90, 80, 70, 60, 50% of full range. (Note: the third 50% point is shown in parentheses since it is taken only when the calibration must be conducted in two halves as is the case when a centrifuge or spin table is used for acceleration input stimulus to a plus and minus range accelerometer.)

The data points are plotted on suitable rectilinear coordinate paper. The abscissa is used for the stimulus input and the output is plotted on the ordinate axis. If the smallest square on the graph paper is either

a 1 millimeter square or 1/20th inch square, then for convenience, it should represent exactly 0.5% of full-scale output and approximately 0.5% of full-scale input. The latter "rule of thumb" applies most specifically to potentiometer output devices nominally rated to have an overall inaccuracy tolerance of, say, ±0.5% to ±3% of full range. The resolution and suitable scale factor for graphs of other devices, such as bridge transducers, should be selected with the idea in mind that the smallest division should represent approximately 0.5% of full range.

An imaginary ribbon of uniform width, having straight parallel edges, is superimposed on the data points such that all data points are just covered by the ribbon. The best straight line sensitivity of the transducer is given by the slope of the straight line which bisects the width of the ribbon. The maximum deviation of the transducer output from the best straight line is given by plus or minus one-half the width of the ribbon properly projected to the input axis to relate the tolerance to a percentage of full range. The maximum deviation percentage thus obtained includes all transducer uncertainties for the standard conditions as applicable.

(6) Dynamic Considerations

In certain cases, it is desirable to establish the ability of a transducer to follow a rapidly varying stimulus input. Many transducers, such as accelerometers and rate gyros, react dynamically in a manner approaching the standard characteristics of an ideal second-order system. If the transducer characteristics tend to conform to a standard curve, the vendor will probably state the nominal natural frequency and damping ratio. The method of laboratory measurement of natural frequency and damping ratio should be agreed upon by the vendor and user. Perhaps if sinusoidal inputs are expected in the actual measurement, these should be used in the laboratory calibration. If transient analysis is more important in end use, then these characteristics may better be observed in the decay curves which result from a step change in the input stimulus. Generally if the damping ratio can be relied upon to stay between 0.6 and 0.8, the devices known to approach second-order systems will produce dynamic data with sinusoidal inputs up to a frequency equal to one-third of the natural frequency with less than ±5% error due to dynamic considerations.

b. Transducer Characteristics (Ref. 288)

(1) Accuracy and Response

The quality of the measurements performed by any instrument is given by its accuracy. This accuracy represents the extent to which the instrument readings approach the "true" values under calibration conditions. "True" values, in this case, are determined by other "more accurate" instruments, and working standards whose accuracy can be ultimately referred back to the prototype national or international standards of length, mass and time.

The accuracy of any instrument is the resultant of all the errors or measurement that play a part in the use of the instrument. Two sources of errors are: the accuracy with which the input to the instrument is known during the calibration, and the accuracy with which the output of the instrument can be measured. It is most desirable to have these accuracies about an order of magnitude better than that of the instrument. If this is true, then the instrument accuracy will be shown by the extent to which instrument readings approach "true" values under calibration conditions. The "accuracy" of an instrument is usually expressed in terms of a "limit of error" and given as a percentage of the full-scale range of the instrument.

There are many properties which influence the quality of the measurements performed by an instrument, particularly a telemetering instrument. Among them are such instrument characteristics as linearity, hysteresis, repeatability, temperature effects, acceleration and vibration effects, and others. In view of the many factors involved, it is meaningless to give one figure of accuracy as an indication of the quality of the measurements possible without going into elaborate detail on all the conditions under which this figure applies. It is preferable to list as many of the instrument characteristics as is possible.

The properties listed above are "steady-state characteristics" obtained from steady-state calibrations with fairly well established methods with the aid of reliable working standards. Since most measurements in telemetering are made of time varying physical quantities, the dynamic characteristics of the instrument will have an important effect on the quality of the measurements. Such dynamic characteristics as frequency

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288 Lederer, Paul S., "General Characteristics of Strain Gage Accelerometers Used in Telemetry," National Bureau of Standards Report No. 6907, July 21, 1960, pp. 18-30.

response, phase response, dynamic linearity, damping factor, distortion, variation of hysteresis with frequency, and others cannot be determined as readily and precisely as the "steady-state characteristics," nor are the methods and working standards for their determination as well established or reliable.

(2) Repeatability

One of the important characteristics of an instrument is the repeatability ("precision" or "uncertainty" are sometimes used to describe the same property). It may be described as the variations in the output of the instrument under steady state conditions when the same constant level of input is repeatedly applied. A value for repeatability will have meaning only if the repeatability of input stimulus and output measurement is (preferably an order of magnitude)better than the repeatability of the instrument under test.

Actually, two types of repeatability exist: short term repeatability and long term repeatability, also called drift. "Short term" generally refers to a period of time of the order of minutes over which the test is performed. Long term repeatability tests may occur over a period of days to months.

(a) Short Term Repeatability

This type of repeatability may be a function of many factors, such as backlash, imperfect elasticity of elastic members, coldworking of elastic members, energy absorption of instrument from the quantity to be measured and minor variations in the local environment.

Tests to determine short term repeatability are performed with steady-state input at other than zero, preferably near full scale. Short term variations of the output with zero input are seldom encountered. When they do occur, the are usually the result of stray pickup or other faults of the output sensing equipment or possibly, in the case of strain gage pickups, a noisy excitation voltage supply.

(b) Long Term Repeatability

This is often referred to as drift. It results from gradual changes in the property of materials, dimensions, and chemical

changes, as well as from changes induced by varied environmental conditions and use.

To determine long term repeatability, repeated measurements of the instrument's output are made over a long period of time with zero input as well as some value of input near full scale. From these data, values of long term repeatability may be given in terms of zero shift as well as sensitivity change (for linear transducers).

(3) Linearity

Linearity is a measure of deviation of the transducer response from a specified straight line. It is important that the straight line be completely specified. Different numerical values of linearity may be assigned to an instrument. They depend on the straight line to which the linearity is referred. There are two common ways of describing the straight line: (a) the straight line connecting the calibration point at zero input to that at full scale input; (b) the best straight line through all of the calibration points. The best straight line in the latter case may be just simply drawn by eye through the calibration points or it may be determined mathematically. The linearity (deviation from the specified straight line) is generally given as being "within some percentage of full scale."

Experimentally, it is not easy to determine linearity precisely. Limitations are imposed by the experimental accuracy of the calibration and the repeatability of the instrument under test. The value of linearity assigned to the instrument cannot be any better than the repeatability. The scatter of experimental data will limit the determination of linearity, so that frequently, the conclusion drawn is that linearity is no worse than the scatter.

(4) Hysteresis

Hysteresis may be defined as the summation of all effects, other than backlash, wherein the output assumes different values for the same value of input when that input is applied in an increasing or decreasing direction.

As in the case of linearity, as long as the instrument operates well within the elastic limits of its components (e. g., springs and strain gages), the hysteresis should be quite small. As above, the short term repeatability of the instrument under test as well as the accuracy of the calibration will limit the precise determination of hysteresis.

(5) Resolution

Resolution is a measure of the degree to which small increments of the measurand can be discriminated in terms of transducer output. That is to say, the smallest change in applied stimulus that will produce a detectable change in the transducer output.

(6) Response to Transverse Excitation

This phenomenon is usually associated with the testing and evaluation of accelerometers. The transverse response of an accelerometer represents the output when acceleration is applied to the instrument in a direction perpendicular to the sensitive axis of the instrument. Generally, the transverse response (also called "cross coupling" or "cross talk") is expressed as the ratio of the sensitivity of the instrument to accelerations perpendicular to the sensitive axis to the sensitivity to accelerations along the sensitive axis.

(a) Transverse Response to Steady-State Accelerations

Much of this transverse response is due to manufacturing tolerances and misalignments during assembly, which cause the true sensitive axis of the transducer to be not quite perpendicular or parallel (depending on design) to the mounting surfaces or other fiducial line. However, even if the transducer is mounted so that the sensitive axis is exactly perpendicular or parallel to the mounting, a minimum amount of cross talk will be present, referred to as "inherent" crosstalk. Crosstalk is also a function of the position of the mass of the spring-mass system. In general, the effect of transverse accelerations on the output of the transducer is apparently greater when there is also full-scale acceleration applied along the sensitive axis than when no acceleration is applied along the sensitive axis.

Since transverse response appears to be greater when accelerations are also applied along the sensitive axis, tests are often performed by applying steady-state acceleration at some known angle to the sensitive axis. This results then in two components of the accelerations; one along the sensitive axis and the other transverse to it. Unless, however, the location of the center of mass of the seismic system is known accurately, the above components of acceleration cannot be accurately determined.

A promising way of determining the steady-state transverse response appears to be one which the manufacturer can perform before the instrument is assembled. A known force (such as a spring) pulling the seismic mass transversely, while weights hanging from the mass simulate acceleration along the sensitive direction, would allow determination of the transverse response quite accurately.

(b) Transverse Response to Vibrational Accelerations

Accelerometers will generally also show a transverse response to vibrational accelerations (sinusoidal or transient) as well as steady-state accelerations. The effects of poor assembly methods during instrument construction may be magnified by resonances. Laboratory measurements of the response to transverse vibrational accelerations on the assembled transducer can be quite good, since only the direction of the sensitive axis need be known.

(7) Temperature Effects

Slow changes in the ambient temperature may affect the operation of transducers by giving rise to zero shifts, changing the sensitivity, and changing the viscosity of the damping fluid (if used), thereby changing the damping ratio and consequently the dynamic response of the transducer.

(a) Zero Shift

Zero shift may be due to unsymmetrical changes in dimensions with temperature or it may be caused by temperature gradients. The amount as well as the direction of zero shift due to slowly changing ambient temperatures are not readily predictable for any transducer but seem generally reproducible for any particular transducer and may be determined by test. It is, therefore, feasible in most cases to reduce this zero shift by a process of temperature compensation. With strain gages, for example, this takes the form of a small resistor, which when added to one arm of the bridge, will undergo a change in resistance with temperature which will oppose the zero shift.

The location of an instrument in close proximity to a rocket engine or to the skin of a high-speed missile may result in the instrument's exposure to thermal transients. The effect of such transients

would probably manifest itself in a zero shift, which would be a function of the magnitude and duration of the transient. Temperature compensated transducers will be affected even more than uncompensated ones if gradients exist between the sensor and the compensating element.

(b) Damping

In the case of fluid-damped accelerometers, damping may be affected by temperature-induced changes in the dimensions of the passages through which damping fluid must pass. Such dimensional changes may be used in some cases to compensate for the change of viscosity of the damping fluid. If an increase in temperature, which results in a decrease in damping fluid viscosity, would also decrease the size of the passages, the damping ratio would not change as much. A practical way of reducing error due to viscosity variations with temperature, as well as other temperature errors, is by the temperature control of the entire transducer. This is done by use of an electrical heater jacket and thermostat. The control temperature is usually in the range of 110°F to 135°F, permitting temperature control of the transducer to be effective up to these temperatures and down to temperatures as low as -65°F. The low temperature limit depends on available heater power, transducer size, insulation, etc.

(8) Environmental Extremes

While all environmental changes affect the measuring accuracy of transducers to some extent, if the environmental changes are severe enough, the instrument may be temporarily or even permanently disabled.

(a) Steady-State Acceleration

Consideration of acceleration overloading is particularly important in strain gage type accelerometers. Exceeding the elastic limit of strain gage wires, springs, or beam material will introduce a permanent "set." In extreme cases, the wires and other parts may actually break or rupture and thereby ruin the transducer. To prevent this, the manufacturer generally builds stops into the transducer to prevent the moving part from traveling more than some nominal percentage beyond its full-scale range.

Accelerations applied parallel or transverse to the sensitive axis of other transducer type may likewise cause a permanent set or rupture. The engineer must take into account the predicted

magnitude and direction of acceleration loading when the transducer is mounted in the intended vehicle. Knowledge of the transducer's construction is essential if he is to decide whether or not a series of acceleration tests are to be performed for evaluation purposes.

(b) Vibration

It is extremely difficult to determine the effect of the environmental extremes experienced by a telemetering transducer in flight on the accuracy of the data obtained from it. This is not only due to difficulties in simulating such environmental extremes in the laboratory, but also due to the fact that it is hard to predict and determine their magnitudes during flight tests. At present, there is disagreement concerning the best way of testing instruments for their tolerance to environmental extremes. In the field of vibration testing, for example, a controversy exists between those who test instruments by the application of sinusoidal vibrations over a wide frequency range, and those who prefer to apply a random noise type of vibration spectrum. The latter method most closely simulates what actually occurs in flight. In addition, while the failure of an instrument due to environmental extremes is quite clear cut, "damage" or "unsatisfactory operation" allows a wide latitude of interpretations. Another difficulty exists in the fact that many cases of failure or "damage" are due to imperfections of materials, poor assembly, improper inspection, and other factors pertaining to a particular instrument but not necessarily to all instruments of the same type or class. Thus, failure of one instrument does not automatically imply failure of others of the same type under similar circumstances.

(c) Acoustic Noise

With the advent of high-power jet engines and rocket engines, high acoustic sound levels generated by them creates another environmental probelm. These high level sound pressures may excite to resonance those structural members on which transducers are mounted, thereby producing vibration effects in the transducers. In one case, it has been reported that an unbonded strain gage accelerometer, when exposed to an acoustic field of about 165 db intensity at 600 cps, showed outputs of the order of 10% to 30% of full scale. This was apparently due to resonant excitation of the instruments' top cover plate and transmission of this vibration to the mass through the damping fluid.

4-3 CALIBRATION OF LINEAR ACCELEROMETERS (Ref. 289, 290)

The performance of an accelerometer can be judged in terms of the following parameters: range, calibration factor, linearity, damping, and natural frequency. The simplest method of obtaining the first three is by means of a static test setup, while the latter two must be determined dynamically.

a. Static Acceleration

For static calibration, two practical methods of subjecting the transducer to a precise acceleration are commonly used. One technique, known as the 2 g turnover method, utilizes the earth's gravitational field as a calibration standard. Holding the instrument with the sensitive axis vertical, a reading of its indication is made; the instrument is then simply inverted and another reading taken. The difference in readings obviously arises from a 2 g difference in acceleration, and a basic static calibration is established. As a further elaboration, the accelerometer may be mounted to rotate about a horizontal axis and, if it has been properly designed to have negligible lateral response, the acceleration applied along the measuring axis will vary as the sine of the rotational angle. Hence, calibration points may be taken continuously from +1 g to -1 g.

Static accelerations higher than 1 g are generated in a centrifuge. The axis of rotation should be vertical so that a ±1 g ripple is not superimposed upon the static acceleration. Care should be exercised to align the sensitive axis of the test instrument on a radius of rotation to avoid shortening of the effective radius. Knowledge of the location of the exact center of mass of the seismic system is imperative. If this information is not available, it may be approximated from data of two or more tests made at the same speed with variations in the radius of rotation. Since the acceleration varies as the square of the angular velocity, the speed regulation is important. Effective systems of speed control include the use of a synchronous motor to power the centrifuge, or utilization of the stroboscopic principle as a means of speed indication.

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289 "Calibration and Test of Accelerometers," Instrument Note No. 6, Statham Laboratories, December 1948.

290 "Basic Method for Accelerometer Calibration," Instrument Note No. 17, Statham Laboratories, September-October, 1950.

In calibration of a linear accelerometer by the centrifuge method, its linearity is inspected by imposing changes of acceleration on the instrument by varying either the radius of rotation or the speed. The static acceleration experienced in runs of this type is found by

$$a = 4\pi^2N^2r/(32.174 \times 43200) = 2.840 \times 10^{-5}N^2r \qquad (4\text{-}1)$$

where r is the radius of rotation of the center of gravity of the active mass in inches, N is the speed in revolutions per minute, and a is in standard g units.

b. Damping and Frequency Response

A convenient method for finding the dynamic response of an accelerometer whose damping is less than critical is to observe the instrument's response to a step function in acceleration. A linear step function for a linear accelerometer can be approximated by suspending the accelerometer from a string over some padding. The string is cut quickly and the initial fall of the accelerometer will result in a step function of 1 g amplitude. In some accelerometers, it is possible to apply a step function by displacing the mass and suddenly releasing it. The value of the damping ratio can be found by measuring the height of the first over-shoot. Figure 4-1 may be used to determine the damping ratio.

It should be noted that the interval between successive peaks of the oscillatory response determines the periods of the free oscillations and not the undamped natural period. Actually, the damping has nothing to do with the natural frequency, but does affect the period at which free oscillations will occur. The undamped natural frequency can be determined from the period of free oscillations by substitution in the following equation

$$f_n = 1/T\sqrt{1 - h^2} \qquad (4\text{-}2)$$

where T is the period of free oscillations, and h the damping ratio. Except for greatly underdamped, low-range accelerometers, this method is not recommended for determining the dynamic response.

For a more precise analysis of the transducer's characteristics, it is necessary to obtain a frequency response curve. The response of an accelerometer to a sinusoidal exciting function is shown in Figure 4-2, where

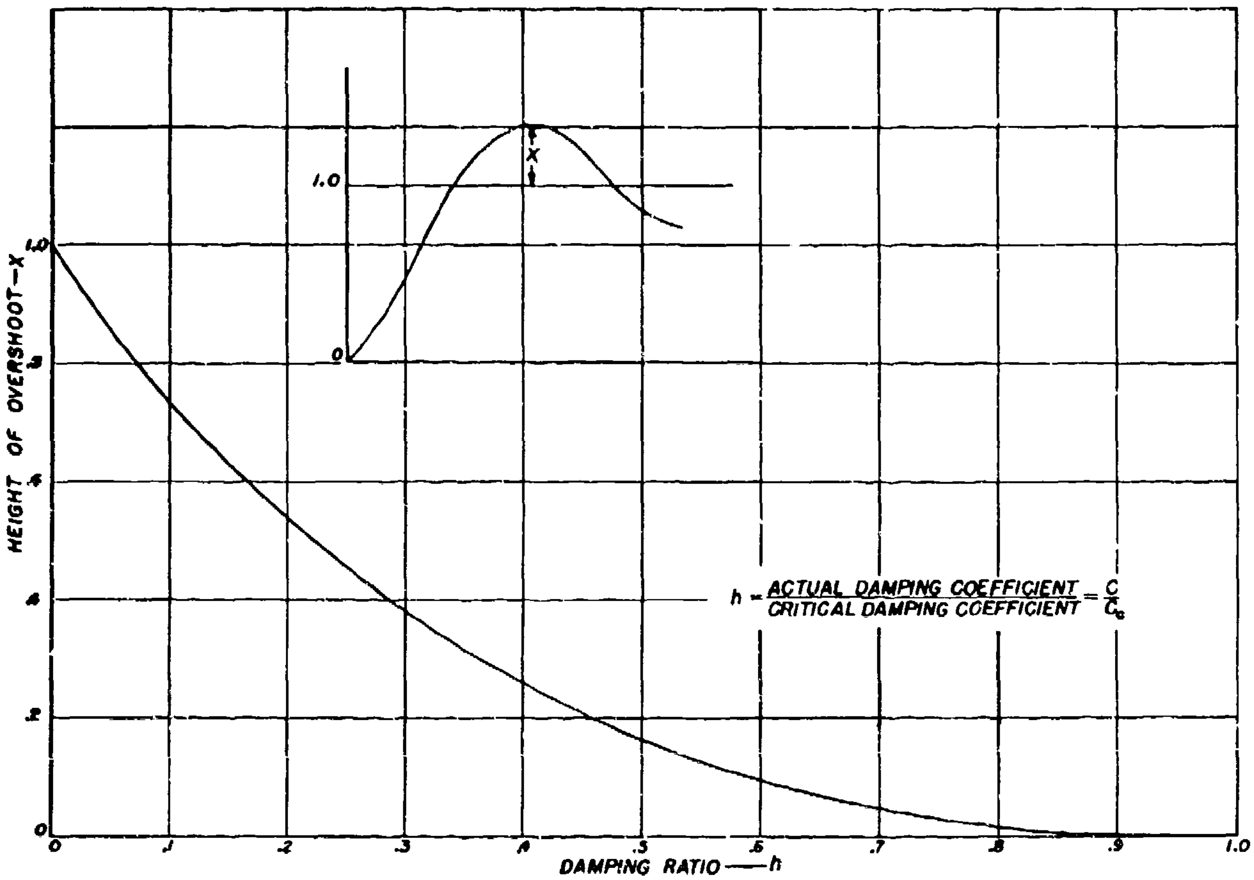

Fig. 4-1. Height of Overshoot of Oscillatory Transients as a Function of Damping Ratio for a System with One Degree of Freedom

f_n = natural frequency

f = the variable frequency

h = damping ratio

If the response of the accelerometer is plotted on the same scale logarithmic paper with relative amplitudes as the ordinates and actual frequency as the abscissae, it is possible to superimpose this curve on the master curves of Figure 4-2 to determine the dynamic characteristics, since the latter are plotted in non-dimensionalized units. To do this, it is necessary to place the instrument response curve in such a position that the

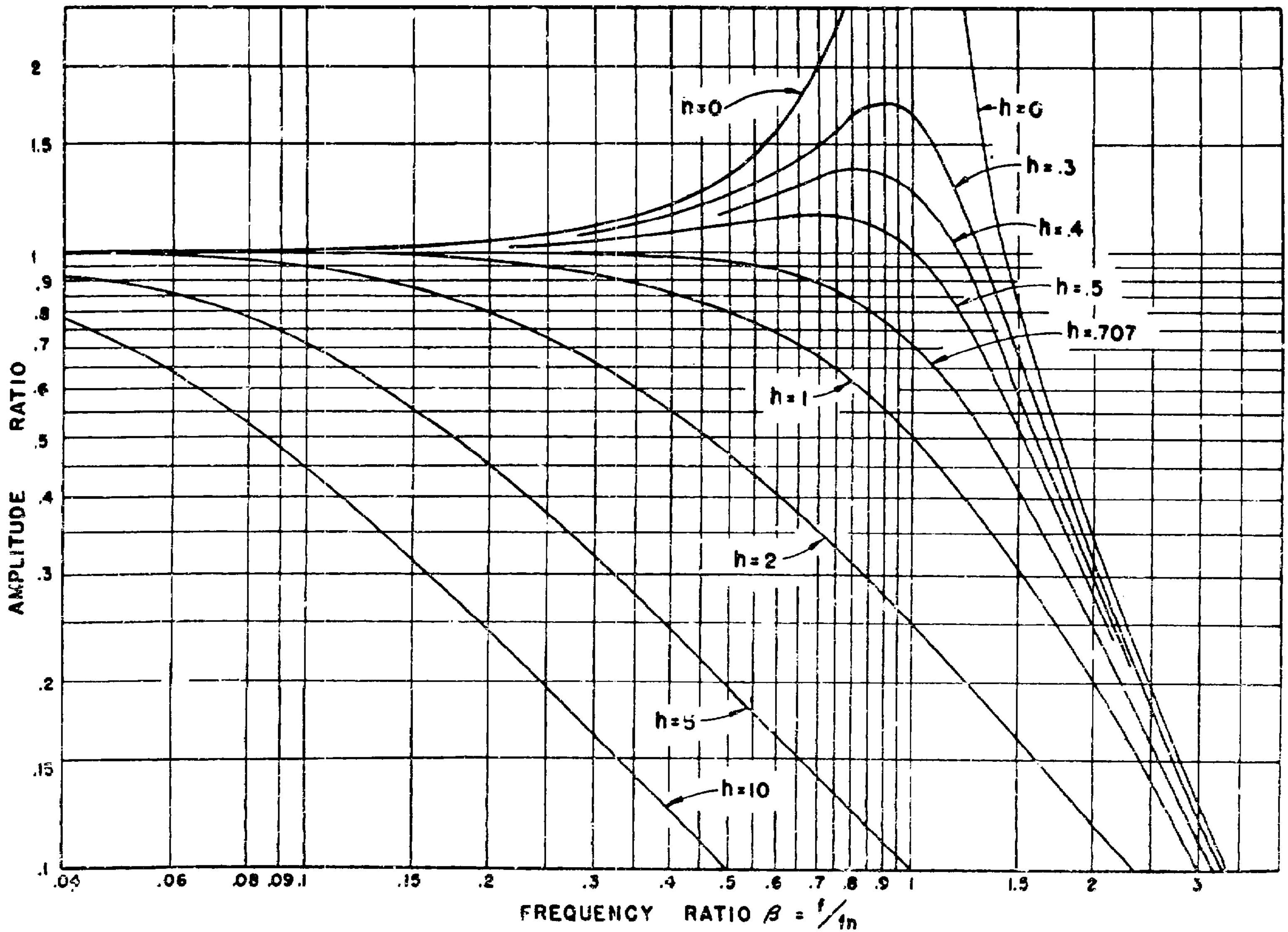

Fig. 4-2. Response of a Seismographic System to a Sinusoidal Displacement

low frequency points lie along the unity amplitude ratio lines and the curvature of the higher frequency points lies between damping ratio lines of greater and lesser curvature, respectively. This procedure is illustrated in Figure 4-3. The damping ratio is then determined by interpolating between the damping ratio lines of the master curves, while the natural frequency is given by the response frequency coincident with the unity line of the frequency ratio of the master curves. In the illustration given in Figure 4-3, this corresponds to a damping ratio of 0.6 and a natural frequency of 600 cycles per second.

The frequency response curve of a linear accelerometer is obtained by calibrating the instrument on a shake table capable of producing an essentially pure sinusoidal force over a large frequency range. While there are many types of shake tables suitable for calibrating an accelerometer, one of the simplest and easiest to use is the electromagnetic type of vibration exciter. The force in this type exciter is generated by an alternating current flowing in a movable coil which is positioned in a region of high magnetic flux density. The magnetic field is derived from a stationary field coil connected to a source of direct current. The shape and strength of the magnetic structure is such as to insure the generated force being dependent only on the magnitude of the current in the moving coil. Since the force generated is as pure as the current supplied to the moving coil, it is necessary to use an oscillator and power amplifier with low distortion characteristics.

To calibrate the exciter, the output of a velocity type signal generator coil, attached to the shake table and moving in the magnetic field of a permanent magnet rigidly supported in space, can be used. The response of the accelerometer can be measured with a vacuum tube voltmeter having a flat frequency response over the range of test frequencies involved.

In a practical test setup, the accelerometer and signal coil are clamped together firmly and attached to the vibration exciter. Since a strong alternating magnetic field will exist about the driver coil of the exciter, it is necessary to isolate the accelerometer and especially the signal coil so that there will be no pickup. This test setup lends itself to a quick and accurate determination of the natural frequency of an accelerometer. The accelerometer and signal coil outputs are connected to the horizontal and vertical amplifiers of an oscilloscope and the frequency at which the two outputs are exactly in phase is the natural frequency of the accelerometer. The oscilloscope amplifiers should be checked for phase-shift error and corrected, if necessary, by introducing a time delay network before the proper amplifier.

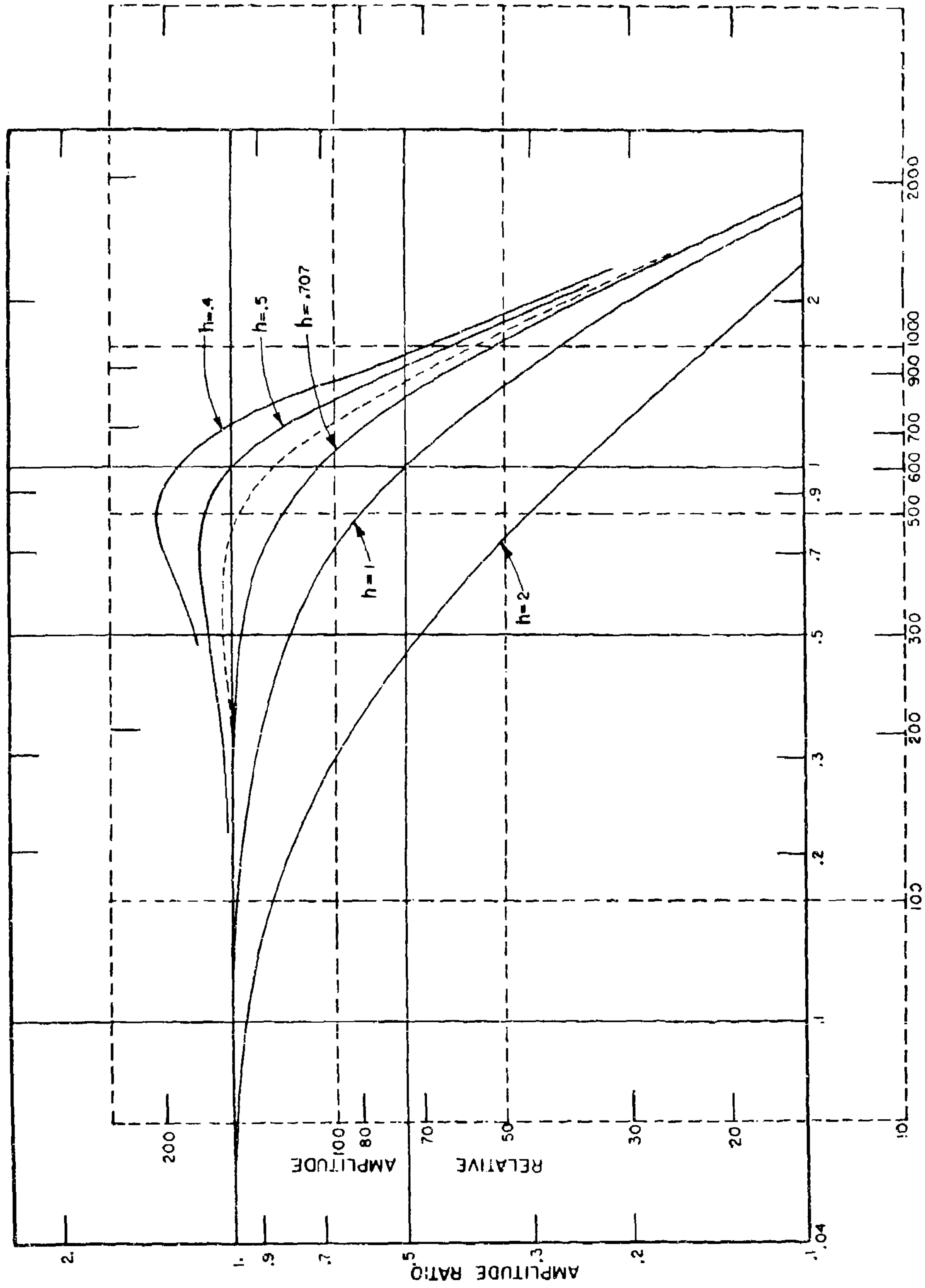

Fig. 4-3. Example of Using Fig. 4-2 to Determine Damping Ratio and Natural Frequency

4-4 CALIBRATION OF ANGULAR ACCELEROMETERS

a. General (Ref. 291)

In the calibration and test of angular accelerometers, the parameters of range, calibration factor, linearity, damping, and natural frequency are usually evaluated on a dynamic basis. A torsional pendulum affords an angular acceleration varying sinusoidally. In practice, the pendulum, with the angular accelerometer mounted on it, is deflected from rest by a known arc and instantaneously set free. The attendant response is recorded. Friction in the system must be of such minor significance that the pendulum oscillates at substantially the same amplitude for several cycles, else determinations must be made of the exact deflection at one particular oscillation. Range, calibration factor, and linearity may be obtained by successive tests at varied initial deflections. Damping ratios of less than unity may be studied by analysis of the record of the first excursion when the torsion pendulum is released. The suddenly applied cosine change in angular acceleration may, in this instance, be considered a step function and the damping ratio determined by the amount of over-shoot by referring to Figure 4-1 which shows the magnitude of over-shoot as a function of damping ratio. The natural frequency of the angular accelerometer must be high compared to the pendulum frequency for the use of this technique. If θ is the initial angle in radians of torsional displacement, and the undamped period of oscillation of the pendulum is T, the suddenly applied acceleration is given by

$$= 4\pi^2\theta/T^2 \text{ radians/sec}^2 \qquad (4\text{-}3)$$

b. Torsional Vibration Calibrator

(1) Description

Two disadvantages of the pendulum-generating harmonic motion method of dynamically testing angular accelerometers are the difficulty of easily varying the frequency of oscillation over the range of interest, and the fact that the amplitude of motion cannot be kept constant. Damping and friction will decrease the motion of the pendulum until it stops. A report by Lederer (Ref.292) describes an electrically-driven torsional vibration calibrator which generates steady-state vibrations to be used for dynamic calibration of angular motion transducers, e. g., angular displacement gauges and

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291 "Calibration and Test of Accelerometers," op. cit.

292 Lederer, Paul S., "A Torsional Vibration Calibrator," National Bureau of Standards Report. No. 4434, October 1955, pp. 1-7.

angular accelerometers. With this method, the amplitude of angular motion can be kept constant at a desired level and the frequency of oscillation can readily be set to the proper value. Figure 4-4 is a photograph of the NBS system. This electrically-driven torsion pendulum is driven by a two-pole dc motor with limited armature rotation (less than a full revolution). While the motor field is dc excited, alternating current is fed to the armature through flexible leads. With its shaft vertical, the motor is mounted on a massive steel baseplate. The shaft carries a table structure on which the transducer to be calibrated is mounted. Two horizontal helical springs under tension are attached to two rigid supports rising from the baseplate on either side of the motor. The other ends of the springs are attached tangentially to the table structure, thus supplying the necessary restoring torque for the pendulum. These springs and the moment of inertia of the armature-shaft and table structure form a mechanical resonant system. An electronic power amplifier fed by a low-frequency oscillator supplies armature current. The angular table deflection is monitored by means of a coaxially mounted rotary differential transformer whose movable core is rigidly attached to the table structure. The stationary transformer coil assembly is mounted on a bracket fastened to the base and a phase-sensitive demodulator delivers an output voltage proportional to angular table deflection. The polarity of the output voltage indicates the direction of table deflection.

(2) System Static Calibration

The static calibration relates angular table deflection from its "zero position" to the recorded output voltage. This "zero position" is that one in which the table is kept by the two springs with no armature current flowing. The actual calibration consists of deflecting the table structure by increments from its "zero position," measuring the deflection of a radius line on the table by means of an optical slide micrometer and recording the output voltage. Angular deflection is computed and plotted against output voltage.

(3) System Frequency Response

Frequency response of this system was checked by continuous rotation of the differential transformer core at varying speeds. The core was disconnected from the table and the demodulator output fed into an oscilloscope with a dc amplifier.

The rotor was first turned slowly by hand, then by a motor, and the oscilloscope trace deflection noted to determine any departure from flat response.

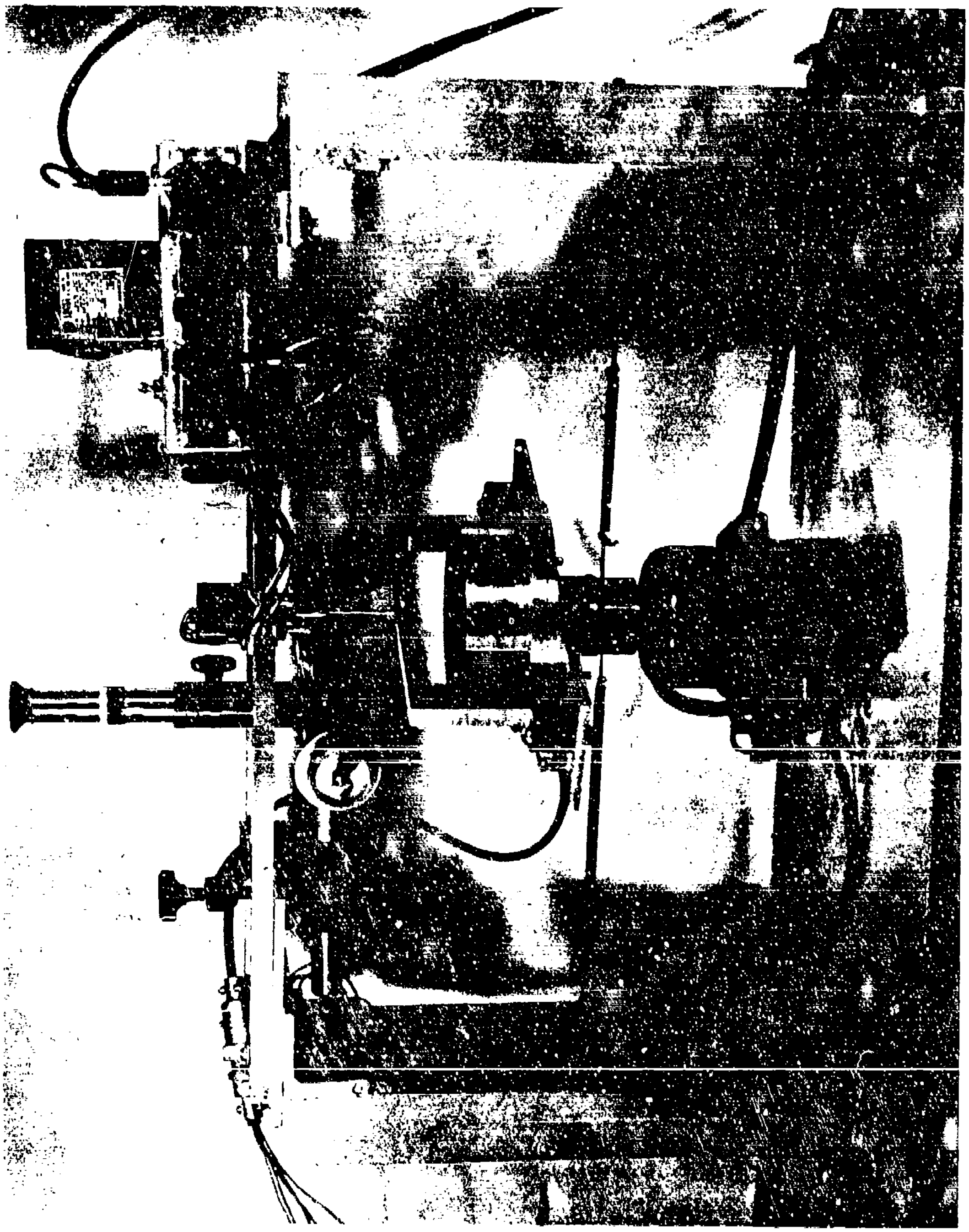

Fig. 4-4. Torsional Vibration Calibrator

4-5 Vibration (Motion and Displacement) Testing Using an Optical Device (Ref.293)

The Model 701 Displacement Follower device manufactured by the Optron Corporation offers a method analysis and calibration of accelerometers, velocity pickups, shake tables and most displacement sensing devices where a time relationship is desired. Figure 4-5 is a functional diagram of the Model 701 device.

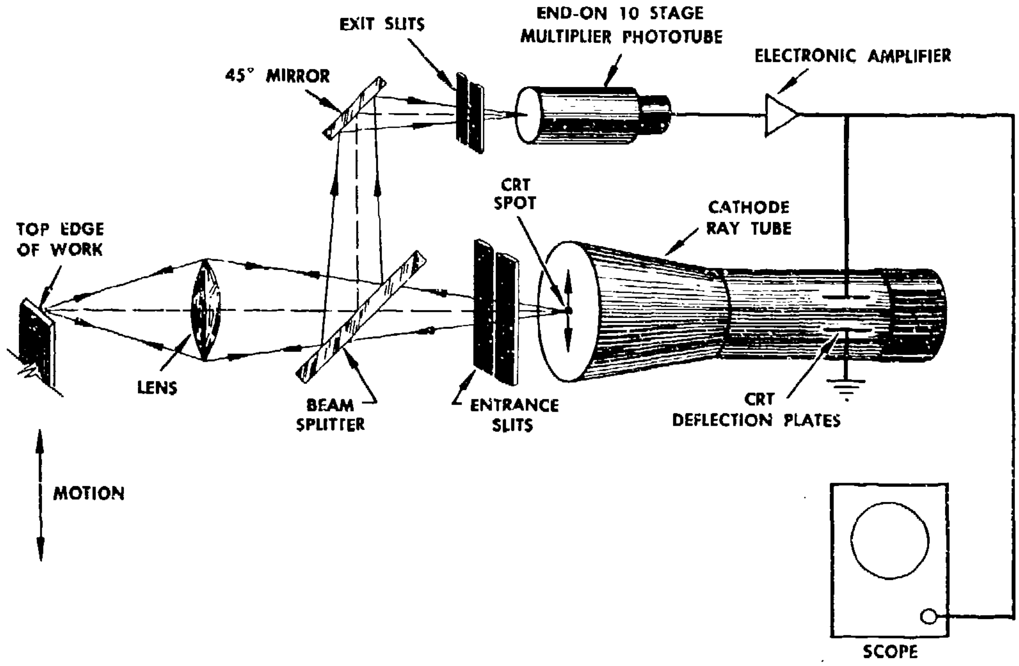

Figure 4-5 Model 701 Diagram of Operation

The instrument focuses a spot of light on the work. A photocell servo system causes this spot to follow the motion of the work. The output presents an exact waveform of the motion. The instrument is accurately calibrated; hence displacement is read directly in inches.

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293 Optron Corporation Applications and Specifications Data Sheet for Model 701.

Light from the CRT spot passes through the beam splitter and is focused by a lens on the work. The servo drives the projected spot until it reaches an edge where it locks on. This servo keeps the spot riding the edge with 50% of the spot diameter above the edge and 50% below.

Any machined surface with a sharp edge may be used as a target, such as the top of an accelerometer or top edge of a shake table.

Hence the spot locks onto the top edge of the work and follows it. The output waveform shown on the scope is an exact duplicate of the work's motion.

4-6 Sweep-Sync Displays for Back-to-Back Transducer Calibration (Ref. 294)

Primary calibration techniques for microphones and accelerometers are difficult and tedious. It is often expedient and satisfactory to calibrate an unknown transducer by back-to-back comparison with a secondary standard. The "Sweep-Sync" can play an important part in dual trace oscilloscope displays of this comparison.

Conventionally, two VTVM's and a phase meter or Lissajou pattern are used to instrument back-to-back calibrations. Complete definition of the output of the unknown requires evaluation of distortion, however, as well as phase and amplitude. With a dual trace oscilloscope under "Sweep-Sync" control, one automated display gives "quick look" data on distortion, phase, and amplitude.

The block diagram Figure 4-6 shows the setup for accelerometer calibration. Amplitude is scaled from the oscilloscope, in preference to a meter, to avoid meter errors on the distorted wave shapes that will be found at some frequencies.

Phase and distortion display is unique and depends on the characteristics of the "Sweep-Sync." This device is a tracking

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294 From Chadwick-Helmuth Co. Technical Bulletin No. 9

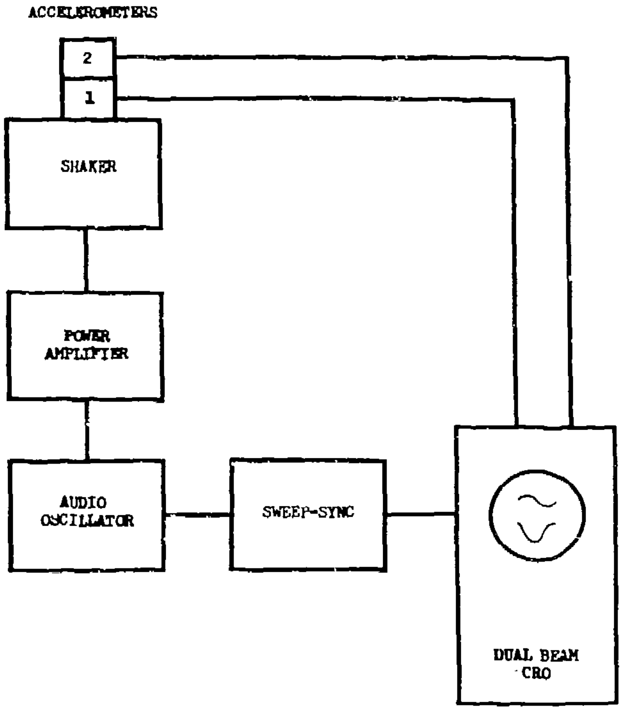

Fig. 4-6 Block Diagram for Accelerometer Calibration

sweep control for a CRO. From 5 to 20,000 cps, it produces a sawtooth with good AVC that is locked in frequency to the fundamental of the signal that it monitors. When this sawtooth is applied to the horizontal amplifier of a CRO, the CRO sweep gives automatically full width display of exactly one cycle, no matter what the frequency. "Sweep-Sync" control can be set to display any number of cycles from one to fifteen. In this application two-cycle display is a good compromise for optimum display of phase and wave shape information.

When the "Sweep-Sync" has been set to 2-cycle display, the sweep width becomes 720° of phase for all frequencies. The gain controls on the CRO can be set for a convenient scale, say 72 deg per cm, and the phase relation between the unknown and the standard is then directly scaled from the CRO as the shift between peaks of the two traces. Dual beam CRO display is preferred to Lissajou for greater accuracy in measuring phase with a distorted signal, and for greater

convenience. Equal gain is not required on the two inputs, and the phase is directly scaled in degrees.

Equal enhancement of distortion is provided. In a conventional CRO display a change in frequency has an accordion-like effect on the display which masks or distracts from a wave shape change. When the X axis is "frozen" by the "Sweep-Sync" control, any wave shape change is distortion or phase shift, and it is more readily detected be it narrow band or broad band. Dual beam CRO display is preferred to a Lissajou pattern so that distortion can be compared between channels.

Since some CRO display is conventional, an additional benefit of the setup is the saving of considerable time other wise spent manipulating sweep controls. On the best CRO's sweep time must be adjusted as frequency is changed. On less expensive CRO's sync controls require attention in addition. No attention to the CRO sweep is required with this method.

This "Sweep-Sync" and dual trace oscilloscope thus make a "quick look transfer function analyzer," and as such are also useful and effective in servo testing.

4-7 Vibration Pickup Calibration

A detailed report on the calibration of vibration pickups (Ref. 295) has been prepared by MB Electronics. Their report describes procedures to determine the calibration constant of a vibration pickup by a comparison method which gives excellent accuracy by minimizing the number of quantities which must be accurately determined during routine calibrations. See Figure 4-7 for functional diagram of the calibration setup. The procedure lends itself to a wide range of frequencies and has been successfully used to 2000 c. p. s. The method is applicable to pickups of the displacement, velocity or acceleration types which are self-generating or equivalent to self-generating types.

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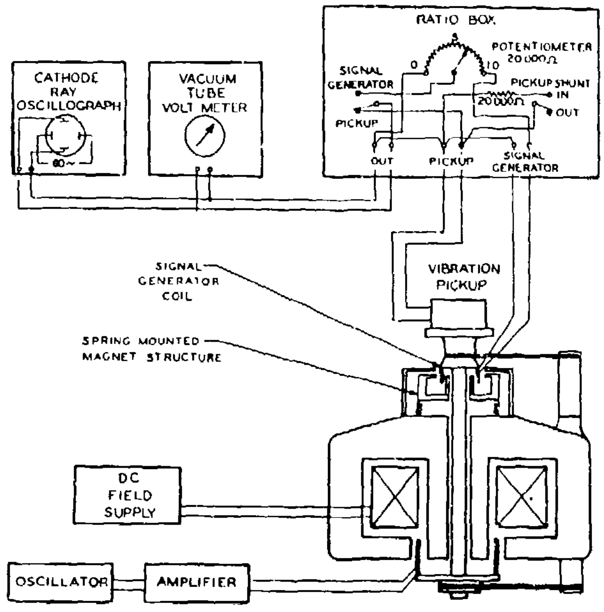
295 Unholtz, Karl, The Calibration of Vibration Pickups to 2000 cps, Manufacturers Technical Bulletin from MB Electronics, A Division of Textron Electronics, Inc.



VIBRATION PICKUP CALIBRATOR

Figure 4-7 Schematic Diagram of Vibration Pickup Calibration Setup.

An over-all calibration of pickup, amplifier and recorder is suggested which is adaptable to all types of pickups. Upper frequency limitations are believed to be the inability to produce linear vibratory motions in the pickup rather than the problem of measuring the motion.

4-8 Use of the SLIP-SYNC in Accelerometer Calibration (Ref.296, 297)

The "streak" or "sandpaper" method of measuring displacement in a calibrating system is very powerful. As opposed to capacity,

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296 Chadwick-Helmuth Company Sales Memo.

297 Bulletins 1 and 12, Journal of Environmental Sciences
June 1959, page 9, "Accelerometer Calibration"
April 1960, page 22, "Back to Back Calibration of Accelerometers."

inductance, or optical follower methods, it is an inexpensive prime dynamic method, and does not rely on intermediate static calibration. It also shows interference by crosstalk. However, it suffers from the inverse square law of diminishing displacement with increasing frequency at constant "g", and has no hope of reaching 2,000 cps, a typical upper frequency of interest in environmental testing today. For high frequency calibration, it yields to the more complex, costly, and tedious reciprocity or interferometer techniques.

The "streak" method fits well with reciprocity and interferometer methods. It is relatively cheap and rapid. Transducers have much more tendency to change their basic sensitivity (millivolts/g), for all frequencies, than to change their sensitivity at certain frequencies. Thus, a quick check at a single low frequency can be reassuring if it agrees with a previous expensive broad band calibration. 50 cps is a popular frequency for this check. It is far enough from 60 cps line frequency to avoid system distortion and amplitude problems, and at 12.8 g vector, it gives 0.100 inch double amplitude. $100 microscopes with 4 inch working distance (as Bausch and Lomb "MACROSCOPE") then contribute 1% or better accuracy to the measurement.

The conventional "streak" method includes a compromise between speed and accuracy. Speed dictates that a dc powered light illuminate the emery cloth target head-on. This results in bright elongated targets, easy to identify and measure with the microscope. However, the streak length is then target displacement plus spot width, which must be measured or estimated and subtracted out. Accuracy dictates that the light illuminate the target almost 90% from the microscope line-of-sight. Spot width is then effectively zero. but the resulting faint traces are barely discernable in the microscope field, and their measurement is painstaking and fatiguing.

Introducing the SLIP-SYNC and STROBEX removes the necessity for the emery cloth target, and removes the compromise. With slow-motion "off" and direct strobe illumination, the moving specimen is "frozen" in the field of the microscope. Invariably tool marks, edges, or markings on the specimen will have contrast and recognition so that the microscope cross hairs can be set to a point effectively of zero width. SLIP-SYNC controls then permit quick "freezing" first at the top of displacement, and then at the bottom,

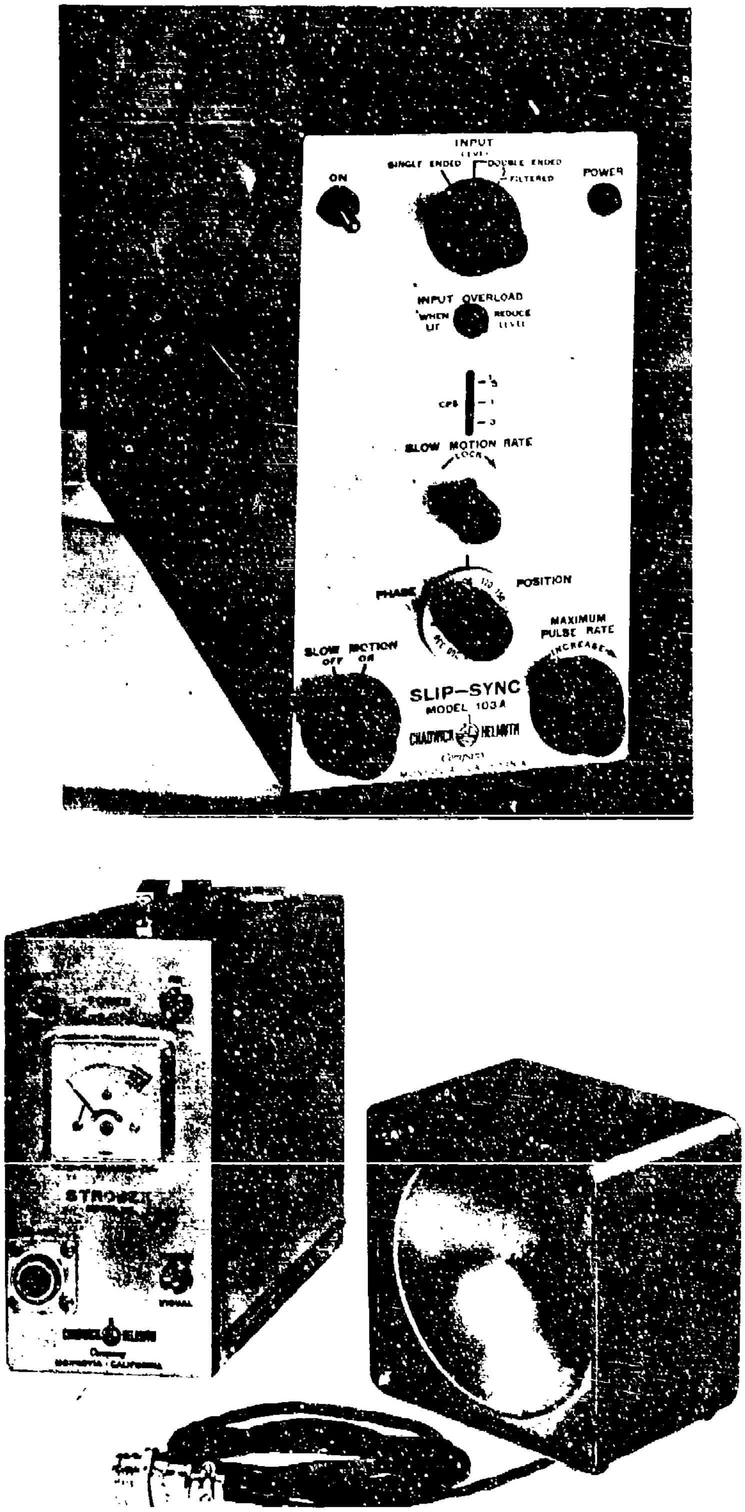

Fig. 4-8 Slip-Sync and Strobex Instruments

for corresponding microscope measurement. There is no spot width error, and the target is bright and convenient to work with. The SLIP-SYNC and STROBEX offer 10% increase in accuracy, and 50% increase in speed, over the "streak" method.

In addition, some recognition is offered of harmonic motion, and amplitude variations, that are very undesirable in a calibration setup. The "slow motion" effect from strobe illumination will be smoothly sinusoidal for sinusoidal movenent. In fact, it is a true slow-motion replica of a repetitive displacement waveshape. Distortion, particularly if it results in local reversals on the waveshape, is recognized with slow-motion "on." Amplitude "off."

4-9 A Vibration Measuring System (Ref. 298)

Oscillograph records of accelerometer signals, showing phase, distrotion, and amplitude, are ideal for analysis of sinusoidal vibration tests. However, the technique has been little used, for these good reasons:

1. Paper speed must be proportional to shaker frequency, and must be continually increased as shaker frequency increases.

2. Paper speeds fast enough for high frequency vibration are not a ailable.

3. Even at modest shaker frequencies, paper consumption is great, and voluminous data defies data reduction.

As a result, a more generally accepted expedient is to record amplitude only, either as an "envelope" on an oscillograph with low paper speed, or as an average, peak, or rms value of the signal on X-Y plotters or oscillographs. Unfortunately, this discards 2/3 of the intelligence carried by modern "hi-fi" accelerometers.

The "VMS" ("Vibration Measuring System") permits continuous and automatic recording and monitoring of phase, distortion, and amplitude. The "VMS" is a sampling system creating a slow-motion replica of accelerometer signals. Any replica frequency from 1/3 to 3 cps can be chosen, and it then remains fixed, even though the accelerometer signal

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298 "A New Vibration Measuring System," Manufacturer's Data Sheet, Chadwick Helmuth Company.

sweeps from 10 cps to 10 kc. The slow-motion replica can be easily recorded on any oscillograph, running at economical, low paper speeds, so that record lengths are quite reasonable. At the same time, the galvos or pen motors can be monitored visually, for "quick look" at phase, distortion, and amplitude.

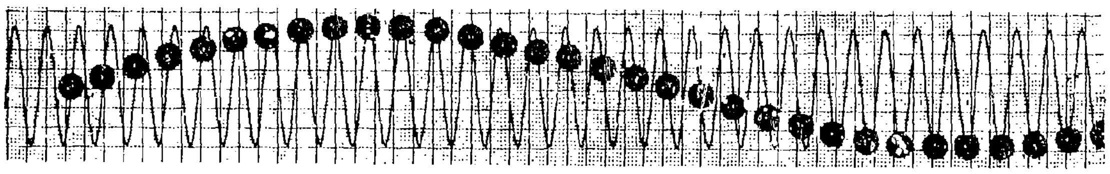
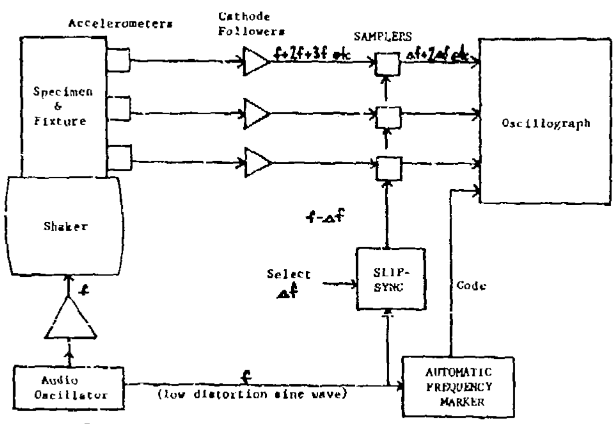


Figure 4-9

Figure 4-9 Slow-Motion Sampling ---The VMS System

Figure 4-9 shows a high frequency sine wave which is the input to a SAMPLER. The large dots represent sample points giving an exact replica of the original signal, at a low frequency.

Figure 4-10 shows the block diagram of a "VMS."



Items in caps furnished by Chadwick-Helmuth.

Figure 4-10

To create the replicas, audio oscillator frequency "f" goes to the SLIP-SYNC. The SLIP-SYNC substracts a difference frequency, " Δ f" adjustable from 1/3 to 3 cps. This "f- Δ f" sine wave is converted to pulses which command the SAMPLERS. This causes successive samples to move progressively thru the wave shape of their input signal, creating a slow-motion replica of that signal at frequency "Δf". The input to a SAMPLER is normally the output of an accelerometer on the shaker or specimen. This accelerometer signal will have a fundamental at shaker frequency "f" and may also have harmonically related distortion, "f + 2f + 3f----". The signal is reproduced faithfully as " Δf + 2Δf +3Δ f---" in the replica.

The "VMS" does not have application in random or noise testing, and in rare cases when transients, noise, or other non-harmonic signals are present in sinusoidal tests the "VMS" will not show them in slow-motion, but will show that they exist.

The SAMPLER output will drive directly moderate frequency light-spot galvos, or will directly moderate frequency light-spot galvos, or will drive the amplifiers for pen motors to produce a permanent record of the waveshape involved. The resulting record has a fixed distance for each cycle on the record, whether it be sample of low, moderate, or high frequency vibration. To make the resulting record completely useful, the AUTOMATIC FREQUENCY MARKER generates coded burst for another galvo in the recorder every two seconds, so that shaker frequency, correct to 4 significant figures is also on the record.

Distortion is an oft-overlooked problem in vibration testing and analysis. High"Q" resonances in the specimen will respond to the harmonic content of the shaker system, amplifying it until it may exceed the fundamental. In extreme cases specimen response at the fundamental may be imperceptable, with input at fundamental frequency, and response at some harmonic of this frequency. In any sinusoidal vibration test there will be frequencies where an rms or peak or average "g" reading is meaningless because it consists of several frequencies.

Phase is a powerful tool in vibration testing. It is essential to calculation of stress between two instrumented points. Two points in phase with equal "g" create little stress, but when they are 180° out of phase considerable stress in created. 90° phase shaft between input and response also defines resonance, and is particularly

necessary in damped systems. Phase shift between two accelerometers with sensitive axes parallel can also warn of crosstalk. It is also essential to the definition of mechanical impedance, as the vector of force divided by velocity.

4-10 Pressure Transducer - General Evaluation Procedure

A set of procedures has been formulated at Edwards Air Force Base in Data Reduction and Processing for the general evaluation of pressure transducers. This information was submitted by Mr. David Limbacher of DRP, and is presented in Appendix V of this manual.

4-11 A Method for Calibration of a Dynamic Pressure Pickup (Ref.299)

The object of this work was to devise a calibration method for a dynamic pressure pickup used during the qualification of the expulsion system and the attitude control system of a guided missile. A calibration fixture was designed, built, and tested at the Chrysler Corporation, Missile Division. The burst-diaphragm method which is employed in the fixture produces a satisfactory calibration curve and can be employed to calibrate transducers of varying capacity which are available from manufacturers.

An Endevco transducer, designed for measuring rapidly changing pressures and shock waves experienced in jet and rocket engines and on the external frames of aircraft and missiles, was tested. This sensor is made from stainless steel and contains a special crystal cut in the shape of a thin, square plate and mounted on three corners. The crystal deflects when the pickup is subjected to a variation in pressure and, as a result, produces an electrical voltage output. This effect is known as the piezoelectric effect. Electric leads attached to the two surfaces of the crystal are connected to the outlet end of the pickup through which the voltage output is conducted to the necessary instrumentation for recording. The pickup is provided with a screw thread and an o-ring and is simply screwed into the wall of the unit in which the pressure measurement is desired.

The instrument indication which is obtained when the pickup is subjected to a variation in pressure is a function of two variables: the voltage output from the pickup and the characteristics of the intervening circuitry.

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299 Holmfeld, J. D., "A Method For Calibration of a Dynamic Pressure Pickup", Technical Memorandum, ML-M61, Chrysler Corp., Missile Div., July 1958.

While the voltage output of the pickup, corresponding to a certain pressure change, can be calibrated by the manufacturer, the cable characteristics will vary in different mounting arrangements and hence the instrument readings will vary in different applications. If the cable capacity is known, the sensitivity of the system may be calculated by use of the formula given in the amplifier manual. If desired, the sensitivity may be standardized by adjusting the capacity switch of the Endevco amplifier. For greater accuracy, however, the manufacturer recommends that the system, consisting of the pickup, the cables, and the instrumentation, be calibrated for each application. The standardization of the meter reading, to show a certain fixed value for a given change in pressure, may be undertaken as part of the calibration procedure.

The calibration is made by subjecting the pickup to a known step change in pressure and recording the instrument output produced. This known step change is obtained by use of the calibration fixture designed for this specific purpose. This fixture consists of a pressure chamber machined in a steel block and an attached diaphragm knife. The chamber is provided with three openings. Through one of these, high-pressure air is supplied to the chamber; and in the other two openings, are placed the pickup and the burst diaphragm.

The chamber is designed with as small a volume as possible in order to obtain the fastest escape of the air and thus the closest approximation to a true step function. For the same purpose of minimizing chamber volume and permitting rapid decompression when the diaphragm is ruptured, the high-pressure air inlet to the chamber is a No. 80 hole (0.0135 in., diameter). The outer connection for the high-pressure air is an AND fitting permanently placed on the fixture and permitting quick connection to the air-control circuit. The best diaphragm material is exposed photographic film, which has the quality of rupturing over its entire pressurized area when pricked with the diaphragm knife. The diaphragm is held by the top plate of the fixture, which is tighened down with four 3/8 - in. bolts.

The high-pressure air circuit is connected as shown in Figure 4-11 The Heise gage must be selected to suit the pressure range over which the pickup is to be calibrated. A block diagram of the electrical circuit as connected is shown in Figure 4-12. The power supply is an

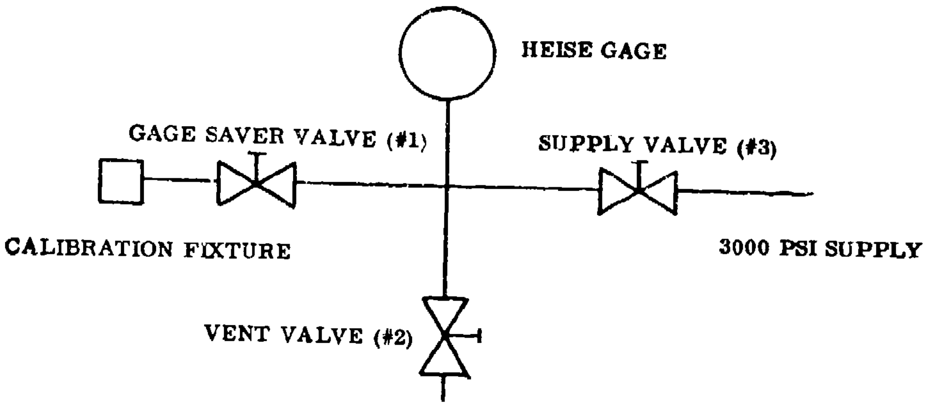

Figure 4-11 High-Pressure Air Circuit

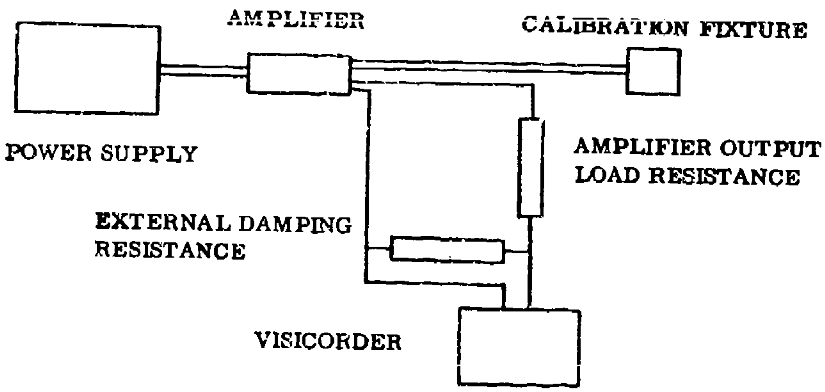

Figure 4-12 Electrical Circuit

Endevco power supply, model 2621, and the amplifier is an Endevco amplifier 2614. The recording instrument is a Minneapolis-Honeywell Visicorder, which provides a permanent record of the output variations. The galvanometer in the Visicorder must be selected according to the pressure range (hence, voltage output range) of the pickup to be calibrated. These galvanometer ranges are given in the booklet "Operation and Maintenance Manual-906 Visicorder Oscillograph" pp. 5-6. The value of the required external damping resistance is given in the same section. The value of the required external damping resistance is given in the same section. The amplifier output resistance must be 2,5000 ohms or greater.

After the transducer has been placed in the calibration fixture and the high-pressure air circuit and the electrical circuit have been connected, the following step-by-step procedure is followed:

1. Place the diaphragm over the top opening and tighten down the cover plate.

2. Open valve 1.

3. Close valve 2.

4. Slowly open valve 3 until the desired pressure in the chamber is obtained as read on Heise gage; then close valve 3. In the event that the pressure in the system exceeds the desired value, reduce the pressure by venting through valve 2.

5. Close valve 1.

6. Start the Visicorder tape.

7. Punch the diaphragm knife to rupture the diaphragm.

8. Stop the Viscorder tape.

9. Repeat the procedure for a new value of chamber pressure.

4-12 Notes on an Automated Pressure Generation and Transducer Calibration (Ref.300)

Prior to the advent of the aerospace age, transducers were used primarily as a research tool and test instrumentation in research programs.

The instrument standard, in factory and flight line testing, for pressure, was the dial indicator type gage operating in accuracy orders of from 1/4% of full scale to 3% of full scale. The standard procedure was that of selecting a specific operating range for the gage of from 50% to 80% of full scale. The high precision and improved reliability transducers has led to the use of large numbers of transducers in missiles as a routine type sensing device.

A manually operated dead weight tester was usually used to test gages and the early vintage transducers. However, when a number of pressure points are required for calibrating a wide range of transducers over their full scale capability, the process of manually placing weights correctly on such a tester becomes a very tedious one and subject to human error by the fatigued operator factor.

The highly automated Model 265 Pressure Transducer Calibrator is a system which can accomplish in 20 minutes what the average technician could manually do in 8 hours.

The Model 265 shown in Fig.4-13 is manufactured by Gilmore Industries, Cleveland, Ohio, and has a system accuracy of ±.05% and will maintain a specific pressure set point over a several day period at ±.05% of the set point value.

The unit is currently being tested as a missile system support item by NASA Marshall Flight Center, Huntsville, Alabama.

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300 "An Introduction to Automated Pressure Generation and Transducer Calibration", Gilmore Industries Data Sheet, 3/13/62.

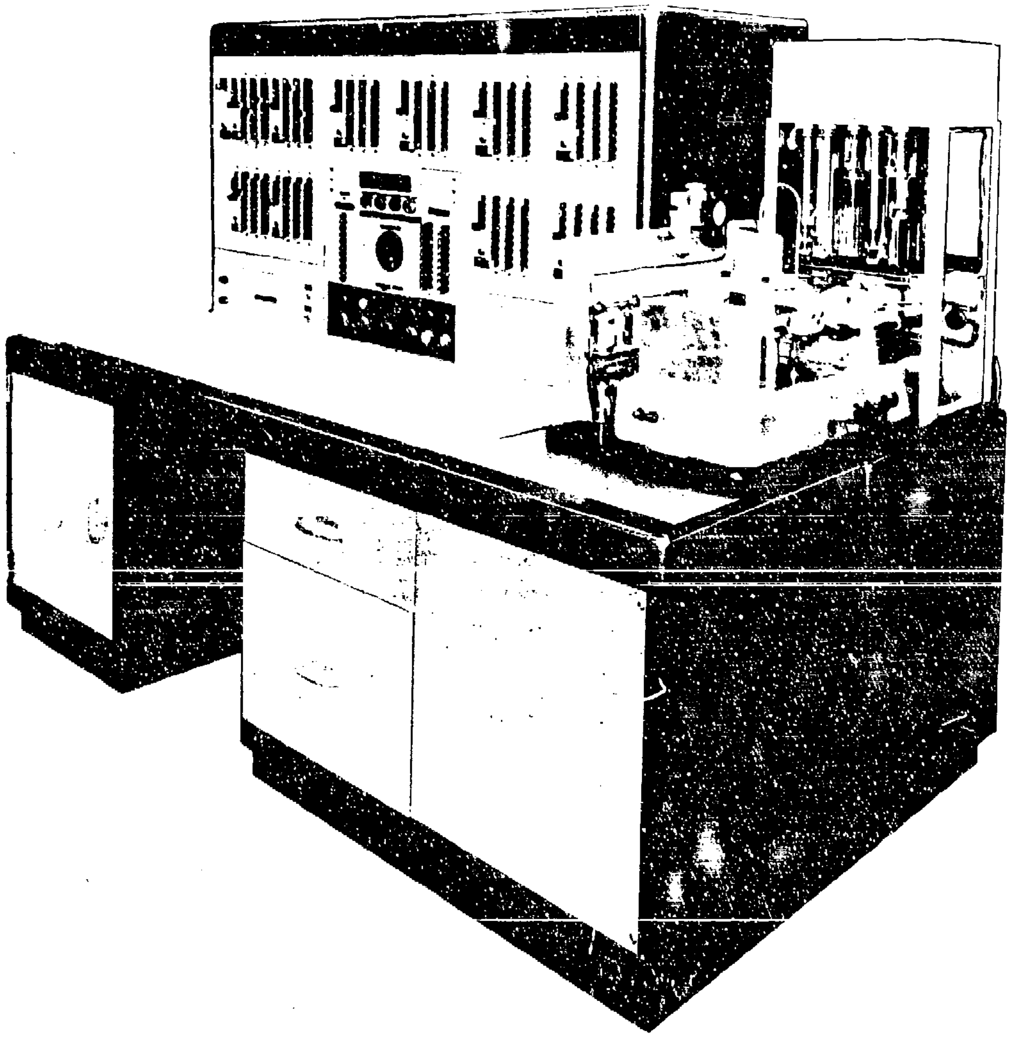

Fig. 4-13 Model 265 Pressure Transducer Calibrator, Gilmore Industries

4-13 Performance Tests on Two Piezoelectric Crystal Pressure Transducers (Ref.301)

The following information from an NBS report illustrates a method of testing and calibration of piezoelectric crystal type pressure transducers.

Two Kistler Instrument Company pressure transducers, type SLM, Serial Nos. 370 and 371 were tested in conjunction with a "piezo-calibrator", Model 2, Serial No. 89, made by some company. Fig.4-14 shows construction of SLM transducers. The purpose of the tests were to determine sensitivity, hysteresis, linearity, repeatability, effects of static and dynamic temperatures, response to dynamic pressures, effects of vibratory accelerations, and time constants of the transducer and calibrator combination.

The quartz pickup and piezo-calibrator combination have a sufficiently long time constant (on the order of 15 minutes) to permit calibration by measuring the charge generated by it when a static pressure is applied. In these gages, the necessary very high leakage resistance is obtained by the use of specially treated quartz crystals, by the use of special high resistance cable, and by very high input resistance of the calibrator (a direct coupled single stage amplifier using an electrometer tetrode). The overall leakage resistance is the order of 10^{14} ohms, which contributes to the very long charge time-constant of this system. In the manufacturer's description of static calibration, the charge generated by a known pressure is exactly neutralized by a charge applied to the "Calibrating capacitor" in the piezo-calibrator from a constant voltage source by means of a built-in precision potentiometer. The electrometer amplifier, together with an oscilloscope direct-coupled to the calibrator output, act as a null detector only; with the resultant calibration being in terms of potentiometer dial division versus applied pressure. The charge time-constant is further increased since the electrometer tube draws off less of the generated charge (in the form of grid current) when that charge is neutralized. When used to sense dynamic pressures, the electrometer circuit acts as an impedance matching preamplifier from the extremely high impedance of the quartz crystal gage to the impedance of a voltage measuring device such as an oscilloscope or vacuum tube voltmeter. The gain of this preamplifier as well as the voltage applied to the calibration

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301 Lederer, P. S., R. O. Smith, Performance Tests On Two Piezoelectric Quartz Crystal Pressure Transducers and Calibrator, NBS Report 4973, February 1957.

potentiometer are fixed by setting the power supply current as indicated on a built in meter to 1.00 ma. In many operations, it is desirable to have zero output voltage when zero pressure is applied to the gage. This is achieved by having a battery in the calibrator between the output terminal and the plate of the electrometer tube connected so as to buck the plate voltage. A fine adjustment for zero output is provided in the form of a small potentiometer (screw driver adjusted) in the calibrator, by means of which the voltage on the grid of the electrometer can be adjusted. This, by changing the current through the tube, will change the voltage at the plate of the tube. However, adjustment of this potentiometer ("output level adjustment control") will also change the gain of the circuit, requiring the recalibration of the piezo-calibrator after each adjustment. Since the static calibration of the system results in a value of PSI/DIAL DIVISION using the piezo-calibrator as a null detector only; this value is independent of the gain of the unit. For the recalibration of the piezo-calibrator is independent of the gain of the unit. For the recalibration of the piezo-calibrator it is necessary only (with no pressure applied to the gage) to move the calibration dial a number of divisions and note the resulting change in output voltage. From this, the change is pressure represented by the measured change in output voltage can be determined.

Both pressure pickups were calibrated statically in terms of divisions of the large calibration dial on the calibrator. A deadweight tester supplied pressures from 10 psi to 1500 psi with an accuracy of ±0.3% of the pressure, while pressures up to 14.7 psi (for the lowest range) were measured to within ±0.5 mm by means of a mercury manometer.

Before each run, the voltage used to supply the neutralizing charge by means of the calibration dial was standarized. This consisted of setting the current through a precision resistor to exactly 1.00 ma by means of the built in rheostat and millimeter. Then, with zero differential pressure applied to the pickup and the calibrator dial at zero, the input to the electrometer circuit was grounded by means of the range switch to remove any charge present. The range switch was then reset to the desired range and the resulting zero pressure response noted on a sensitive dc oscilloscope coupled to the output of the calibrator. The desired pressure was then applied to the pickup and the scope trace brought back to its zero points. Pressure was applied in about ten steps for each range, between

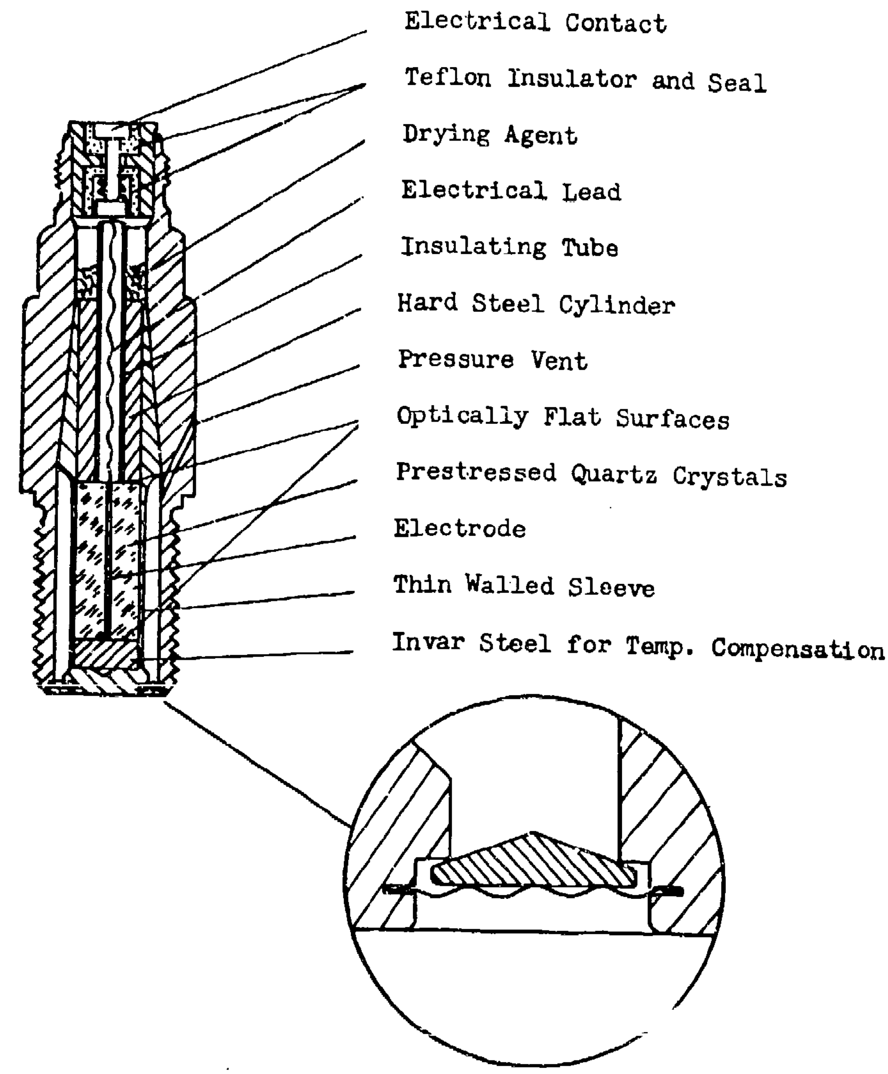

Fig. 4-14 SLM Transducer Construction, Kistler Instrument Company.

zero and full scale. The values of sensitivity in PSI/DIAL DIVISION were obtained from the slope of the best straight line drawn through the calibration points. The limits of calibration accuracy using the deadweight tester are estimated at ±0.9% of the reading. The limits of calibration accuracy using the manometer are estimated at ±0.7% of full scale By repeating one point near full scale from three to five times, values of short time repeatability were obtained. Finally, except on the lowest range, pressures were applied in the following sequence in order to determine hysteresis; 0.1 of full scale, 0.5 full scale, full scale, 0.5 full scale and 0.1 full scale. Maximum observed hysteresis occurred at 0.5 full scale. The limits of calibration accuracy using the deadweight tester are extimated at ±0.9% of the reading.

Pressures below atmospheric were applied to the gage by means of the laboratory vacuum line and measured by a mercury manometer. The output of the piezo-calibrator (15 psi full scale range) was measured on the screen of a direct coupled oscilloscope. The scope was calibrated by means of the calibration dial of the piezo-calibrator. Limitations of the vacuum line prevented going beyond 490 mm Hg.

The SLM pressure transducer was also calibrated independently of the piezo-calibrator in terms of generated charge per unit of pressure by the use of a commercial electrometer (Kiethlet 200 A) and precision capacitor (GR 722D). As before, accurately known values of pressure were supplied by the deadweight tester. When the electrometer is connected to the transducer by its cable, the applied pressure will generate a charge in the transducer. This charge will be distributed on the capacitor formed by the quartz crystals as well as the capacitor representing the cable, its connectors, and the input capacity of the electrometer. Since the electrometer measures the voltage across the latter capacitor, it is only necessary to know the value of this capacitor in order to compute the charge sensitivity of the transducer.

The dynamic pressure calibration was done by means of a shock tube. Step functions of pressure with a rise time of much less than a microsecond and amplitudes ranging from about 50 to 320 psi were applied to the transducer flush mounted in the end plate of the shock tube. The resulting output from the calibrator was photographed from

the screen of direct coupled oscillograph. After each "shot" the oscilloscope deflection sensitivity was determined in terms of divisions of the calibrator calibration dial. From the photograph of the deflection sensitivity was determined in terms of divisions of the calibrator calibration dial. From the photograph of the deflected scope trace and the static calibration of the gage (in psi per dial division) the pressure sensed by the SLM gage was computed. The shock amplitude was computed from shock front velocity determined from the transit time, measured to within ±10 sec., of the shock wave between two fixed barium titanate gages mounted a known distance apart in the shock tube wall.

SLM Gage No. 371 was tested for temperature effects by inserting it in a temperature controlled chamber in such a manner that the cable end of the gage as well as the cable itself were not subjected to the test temperatures. The gage was screwed into a threaded pressure fitting connected to the source of pressure and a mercury manometer. A thermocouple was inserted into the air vent in the gage body. With the calibrator in the 0.5 range, pressures of 200 mm Hg and 700 mm Hg were applied and the output determined as a function of calibrator dial divisions using a direct coupled oscilloscope as null detector.

To study the effect of rapid temperature changes on the gage, the following experiments were performed: With the diaphragm of gage No. 371 exposed to the air at room temperature (74°F, zero pressure), the calibrator output (15 psi range) was displayed on the screen of a direct coupled oscilloscope, with a very slow sweep. The gage was then rapidly immersed to a depth of about 1/8" in a large bowl of water at 118°F. The output on the scope showed an exponential change which leveled off at the equivalent of -15.5 psi after about 125 seconds (the direction of this output change being opposite to that of a positive pressure applied to the gage). At this time with the gage still immersed, the output gradually moved back at a rate which, if extrapolated, would return it to its original value in about 450 seconds. Thus the time required for the temperature compensation of the gage to be effective to the above temperature change appears to be 575 seconds or almost 10 minutes. The gage was then screwed into a dural block with its diaphragm exposed. The flame of a Meeker burner (about 1300°F) was brushed across the diaphragm, in from about 0.2 to 0.5 second. The output on the scope showed a sharp dip (of the order of - 2 psi on the 15 psi range) in the same direction before. Then the output returned to its original position in about 125 seconds. A second run, observed with the fast sweep showed the rise time of the sharp dip to be a little less than 100 milliseconds.

To test for vibration effects, the SLM gage was mounted in a threaded block on the table of an electromagnetic shaker and subjected to vibration peak amplitudes of 5 to 10 G's over a frequency range from 50 to 1200 cps. Two braium titanate accelerometers were inserted on the same block oriented so as to sense extraneous table motions. Frequencies at which the amplitudes of such motions exceeded about 10% of the axial table motion were avoided. The cable connecting the gage to the piezo-calibrator was fastened to a bolt in the shaker body with about 10" of the gage end unsupported. The cable itself was tested by inserting an insulating wafer between the center terminal of the SLM gage and the center terminal of the cable connector. The equivalent output due to cable vibration did not exceed 0.002 psi 0-peak/G 0-peak over the above frequency range.

Each gage was tested by applying vibration in two directions: in the pressure sensitive direction (along the gage's longitudinal axis) and in a transverse direction.

4-14 The Shock Tube as a Facility for Dynamic Testing of Pressure Pickups

Recent rocket-motor developments emphasize the previously existing need for better dynamic pressure measurements and consequently for better means of evaluating gage or pickups intended for such measurements. Gages for such purposed are usually small flush-diaphragm pickups employing the strain-gage, capacitance, variable inductance or piezoelectric principle. In rocket motors there are pressure changes exceeding 200 psi at frequencies exceeding 10 kcps. The dynamic properties of an instrument may be expressed as a plot of the instrument's response to a step-function input, or as a frequency response curve. While the latter is usually considered easier to interpret, it is difficult to obtain the necessary accurately-known sinusiodal input when it must be in the form of a pressure. Step-function inputs of known pressure are more readily produced. Analog computer techniques have been described for deriving frequency response curves from step-function records.

Presently available methods of producing sinusiodal excitation of the gage fall far short of the above figures (200 psi at 10 kcps) in either amplitude or frequency or both, so that direct determination of frequency response curves is feasible only to relatively low frequencies and pressures. A precisely known step change in pressure can be produced by opening a valve, breaking a bottle, or by means of a burst diaphragm calibrator, but the rise times of such negative-going steps are long in comparison with the period of a 10 kcps wave so that the response of gages to such rapid pressure changes cannot be studied by these means.

A step-function for dynamic testing of pressure gages requires the change from one known pressure level to a second known level in a time sufficiently short to shock-excite the gage under test, each pressure level being maintained for sufficient time to obtain a steady record of the gage response. The shock tube meets these requirements well for the testing of very fast gages, i.e., well-damped gages of high natural frequency, but for the testing of gages which require more than 1 msec to attain steady state response after the step change, precise use of the shock tube is limited to low amplitude steps, Rise times around 10^{-9} sec for a positive pressure step can be realized and the amplitude of the step can be determined from the static measurement of initial pressure or, more precisely, from the measurement of the velocity of the pressure wave. The time during which the higher level can be maintained appears to be limited only by the length of the tube although actually the time during which it can be considered constant it rather short, this time decreasing with increase in amplitude for a given shock tube. The amplitude of the step is easily controlled from a few psi to about 600 psi in a shock tube of relatively simple design and inexpensive construction.

Detailed discussion of the shock tube phenomena and its usage may be found in Refs. 302-6.

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302 Glass, I. I., Martin, W. & Patterson, G. N. "A Theoretical and Experimental Study of the Shock Tube", Univ. of Toronto, UTIA Report #2, 1953.

303 Emrich, R. J. and Peterson, R. L., "Pressure Variation with Time in the Shock Tube", Lehigh Univ. Tech. Report #7, 1956.

304 Wolfe, A. E. "Shock Tube for Gage Performance Studies", Report No. 20-87, JPL Cit., 1955.

305 Varwig, R. L., "An Optical Shock Velocity Measuring System for the Shock Tube", NAVORD Report #3901, 1955.

306 Smith, R. O. and P. S. Lederer, "The Shock Tube as a Facility for Dynamic Testing of Pressure Pickups" National Bureau of Standards Report No. 4910, March 1957.

4-15 Load Cell and High Capacity Force Devices

Load Cell calibration is required to accurately establish the transducer characteristic separate from the test stand fixtures and recording system. In this type of calibration, a known load is applied to the transducer and the output is measured with the calibrator. To assure transducer calibration accuracy, the accuracy of the calibrator should be made many times that of the recording equipment used in the actual test. Transducer characteristics such as linearity, hysteresis, sensitivity, factor, temperature effect, side loading errors, etc. are determined during this calibration. Once the transducer characteristics are established, electrical calibration of the recording system can be accurately and conveniently used to check the direct system calibration. Separate calibration of any type of transducer is required -- even if direct system calibration is used in the test cell -- because transducer hysteresis and creep are not apparent during the system calibration. This would, of course, result in considerable uncertainty when trying to achieve thrust system accuracies of plus or minus 0.5% and better.

A number of methods of applying load to the transducer are available, depending upon the accuracy desired and the range of the load cell.
Some of the available methods are as follows:

1. Hydraulic loading with applied force computed from the pressure applied to a piston. The Pressure applied is read on a dial gage.

2. Hydraulic loading with the applied force measured by an NBS calibrated load cell or proving ring in series with the transducer.

3. Platform scale modified to apply a known load on the transducer.

4. "Dead Weight" applied directly to the transducer. (Ref.307)

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307 "Description and Specifications of Model 344 series M and S, Tension-Compression Load Cell", Allegany Instrument Company, Inc. Cumberland, Maryland.

The National Bureau of Standards is the source for standards of mass in this country. The NBS has two dead weight machines, one of 10,000 lb. capacity and a second of 111,000 lbs. capacity. (The two dead weight machines will operate in either compression or tension). They state that these weights are accurate to .02% of reading. Above these weights proving rings are the standard of force. The following ranges of force calibrations can be made at the Bureau. (Ref.308)

a) 0 to 10,000 lbs. with an accuracy of .02% of reading. Tension and compression.

b) 0 to 111,000 lbs. with an accuracy of .02% of reading. Tension and compression.

c) 111,000 to 300,000 lb. using three - 100,000 lb. compression proving rings. Accuracy, 0.1% (compression only).

d) 300,000 to 900,000 lbs. using three - 300,000 lb. proving rings. Accuracy 0.1%. The 300,000 lb. proving rings cannot be calibrated directly in the dead weight machine so they are one more step removed from the .02% dead weights. By using three carefully calibrated 100,000 lb. capacity proving rings in parallel test loads from 111,000 lb. to 300,000 lb. can be measured at NBS within 0.1% With three 300,000 lb. capacity proving rings in parallel test loads from 300,000 lb. can be measured at NBS within 0.1%.

e) 900,000 lb. to 1,500,000 lbs. (compression only). Five 300,000 lb. proving rings are used here. The NBS has not stated the accuracies obtained.

NOTE: The NBS will calibrate only in compression over 111,000 lbs.

The use of proving rings has long been the standard of high capacity forces, but to verify 0.1% or .05% systems encountered in the

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308 Carleton, R. J. Jr., "Precision High Capacity Force Standards" ISA Conference Sept. 1960, ISA Preprint No. 36-NY60.

missile industry (and commercial scales as well) they are considered inadequate not only because of lack of compliance with the two to one ratio required, but more importantly perhaps, the large human element involved in achieving the 0.1% accuracies of which they are capable. A proving ring must be used at a known, stable temperature, and requires considerable skill on the part of the operator in obtaining zero load and loaded condition readings, not to mention the possibility of errors that arise in data reduction to obtain true load readings. A good example of this has been repeatedly observed at the National Bureau of Standards itself in the calibration of high capacity load cell systems, where the first 100,000 lbs. of calibrating is done in the dead weight testing machine, and higher loads are verified against proving rings. Invariably, the data will be smooth or repeatable up to 100,000 lbs., with a considerable scatter of data when switching to proving rings for the higher load calibration.

There is one further element of doubt, and that is the difference in characteristic of a proving ring when loaded square as a single column load test in the dead weight machine, as compared to being loaded with a flat top plate supporting three proving rings. There is always bending in the upper plate when a single 300,000 lb. proving ring is compared with three - 100,000 lb. proving rings spaced below. Since the calibration is a transfer calibration there is always another element of error that must be added to the individual 100,000 lb. proving ring errors. We have found in testing load cells that this bending of the upper plate has an effect on load cells. The effect of eccentric loads on proving rings was reported in National Bureau of Standards Circular C454 (1946).

The National Bureau of Standards has received an appropriation for dead weight testing machines of higher capacity. Machines of 1,000,000 lbs. are in discussion, but completion date is estimated to be in 1963. This means that for the next three years, the proving ring systems referred to above will be the United States basis for high capacity force calibration.

Four systems are mentioned here, suitable for laboratory standards in force measurement. Each system makes use of a hydraulic loading cylinder and frame with the following measuring devices: (Only Electric Load Cells will be covered in detail).

1) Proving Rings

2) Hydraulic Capsule

3) Lever Scale

4) Electric Load Cells

Gilmore Industries is currently processing a contract for a one million pound capacity unit of the electric load cell type, Figure 4-15 . Basically, this is a testing machine configuration specially desinged for force calibration, utilizing a bonded strain gage load cell measuring system with digital readout as the standard. Such a unit has a verifiable accuracy of .05% of the applied load. Because of the limitation in dead weight calibrating capacities at the Bureau is 100,000 lbs., no individual load cell element exceeds this capacity. Multiple cells, physically paralled and totalized on one indicator, are used in the machine. For verification, they are stacked in physical series on the Bureau's 100,000 pound dead weight machine, and by this method .05% accuracy up to one million pounds can be verified. The Bureau's machine has an accuracy of .02% (Ref. 309) This approach has the advantage of being able to readily verify the removable measuring standard by shipping to the Bureau for periodic checking, simplified direct digital readout to eliminate human error, and a considerably lesser investment than a full-fledged dead weight testing machine.

It should be noted that the load cell standard system discussed here in officially listed as the field force reference standard by both the Air Force and the Navy in the following references: Ref. 310 and 311.

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309 National Bureau of Standards Circular C446 (1943).

310 Air Force Technical Order No. 33-1-14 dated 21 August 1959, in Appendix IV, Section 4A-2, Item 61.

311 "Standard Laboratory Instruction Manual" put out by the Navy Standards Lab. at Pomona and listed in Appendix A, dated 19 July 1959, as Item 29.

The equipment consists of the following items:

1) A one million pound compression hydraulic frame (Figure 4-15)

2) Three units of five - 100,000 lb. compression cells and a 500,000 lb. digital summing type force indicator.

3) Three units of a 100,000 lb. Universal Cell each with a digital Model 170 force indicator.

4) Three units of 25,000 lb. Universal Load Cell and each with a digital Model 170 force indicator.

5) NBS calibration on all of the above equipment.

The system will handle .05% of reading from 5000 lbs. to 1,000,000 lb. by use of three sets of load cells and indicators. The items 3 and 4 are straight forward, one handling up to 25,000 and the second from 25,000 to 100,000 lbs. The press is arranged to handle tension and compression with a double acting hydraulic cylinder and the Universal Cells. The "Standard Cells" are screwed to the base of the machine and the rod of the hydraulic cylinder mountea on the adjustable cross head.

Electric load cells are used to weigh the Atlas Missile in tanking on the test sites in Cape Canaveral, Florida (See Fig. 4-17) It is desired to very accurately weigh the entire missile and also the fuel that is added before a firing. The working weighing system consists of four 100,000 lb. cells connected by 1,000 ft. of cable back to the clock house where a digital force indicator reads the total weight on the cells. These weighing systems have been in operation since 1957. As the cells are located only a few feet from the flame from a missile under test, and are flooded with flame as a missile takes off in a flight test, there is always the suspicion that damage has occurred in the weighing system. Several means of calibration were considered such as dead weights, proving rings, water tanks, hydraulic loads, and electric load cells. Since accuracy was of prime importance and the weighing of the fuels into the missile is the only true and basic way of getting the right amount of fuels into the missile, some type of force calibration means was required. Figure 4-19 shows a sketch of the launcher frame and the way it is supported on four vertical cells. A system, as shown in Figure 4-20 was built to calibrate in the field the entire stand and, if desired, with a missile erected, the entire system. Figure 4-20 indicates the principle used is the application of a

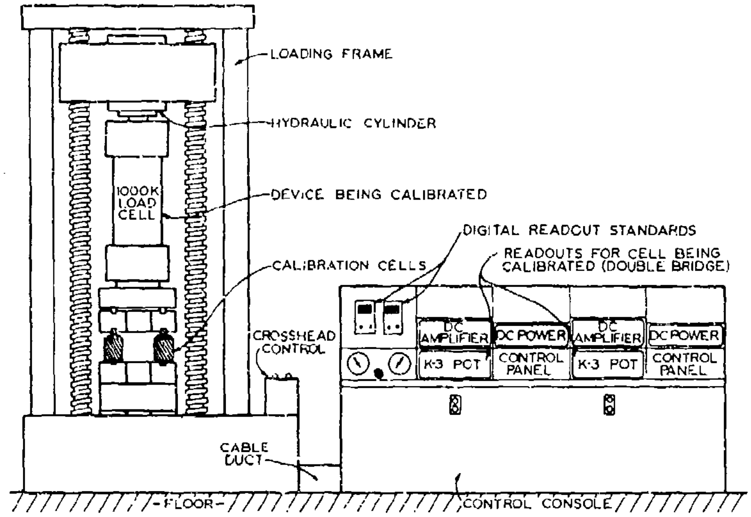

Fig. 4-15 Load Cell Calibrator, 1,000,000 lb. Capacity.

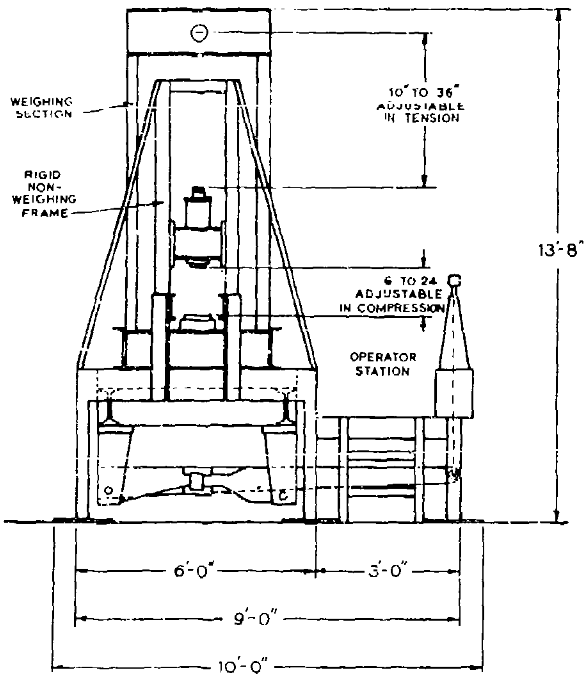

Fig. 4-16 Mechanical Lever Type Scale for Secondary Force Standard.

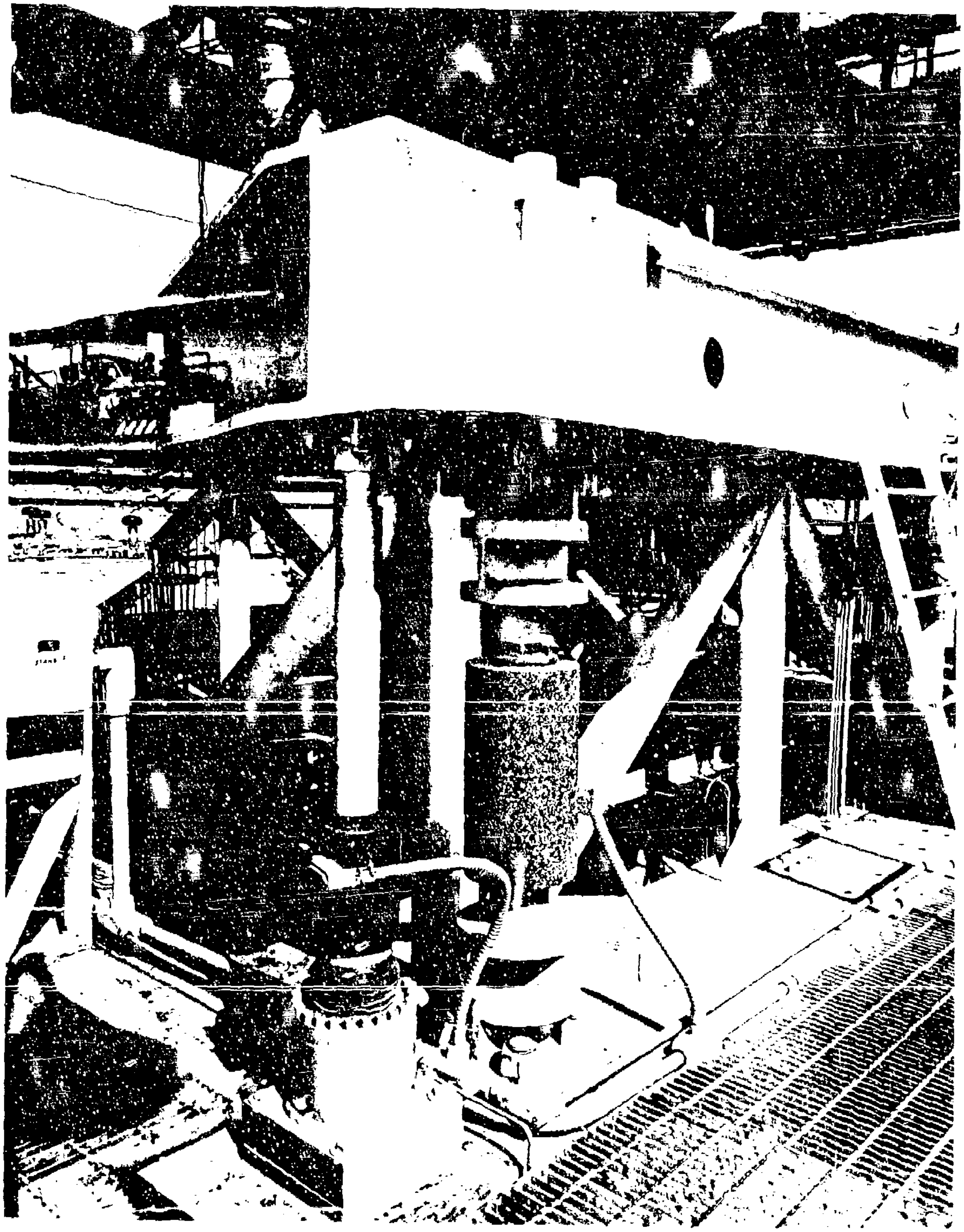

Fig. 4-17 Electric Load Cell Weighing of Atlas Missile

Type System		Min. Div Lbs.	Repeatability	Overall Accuracy	Means of Calibra.	Ratio of Readout Acc to Primary Accuracy		Approx Installed Cost
1) Proving Rings *(Secondary Standard)	a) 10 - 100,000 lb. Rings Or		±0.05%	±0.10%	Primary NBS ±0.02% Dead Weights	5 to 1	Very slow and difficult. 10 operators, not direct reading.	$95,000
*Tertiary Standard	b) 4 - 500,000 lb. Rings		±0.05%	±0.15%	Secondary ±0.1% NBS Rings	1.5 to 1	Very slow and diffi cult 10 operators, not direct reading.	$90,000
2) Hydraulic Cell *Tertiary Standard	1 - 1,000,000 lbs. capsule	1000	±500 lbs.	±0.2%	Secondary 10 Proving Rings ±0.1%	2 to 1	Easy Parallax errors. Direct Reading.	$90,000
3) Lever Scale *Tertiary Standard	1,000,000 lbs. Lever & Beam	20	±0.02%	±0.15%	Secondary 10 Proving Rings ±0.1%	1.5 to 1	Easy but slow. Direct Reading	$140,000
4) Electric Load Cells *Secondary Standard	10 - 100,000 lb. load cells with 2 indicators	50	±0.02%	±0.05%	Primary NBS ±.02% Dead Weights	2 1/2 to 1	Fast and easy. Direct Reading digital.	$100,000

*Note. "Secondary Standard" indicates one step removed from NBS primary dead weight.
"Tertiary Standard" indicates two steps removed from NBS primary dead weight.

Fig. 4-18 Comparison of 4 Types of 1,000,000 lb. Secondary and Tertiary Force Standards

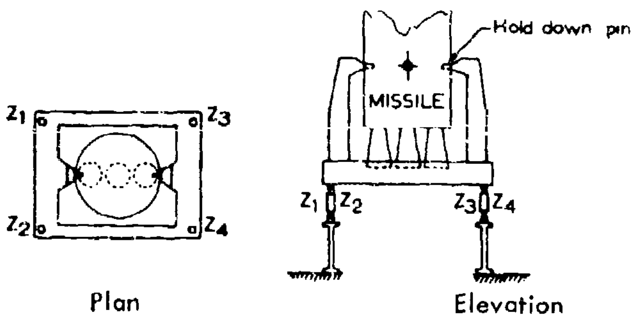

Fig. 4-19 Load Cell Arrangement for Force Component Measurement

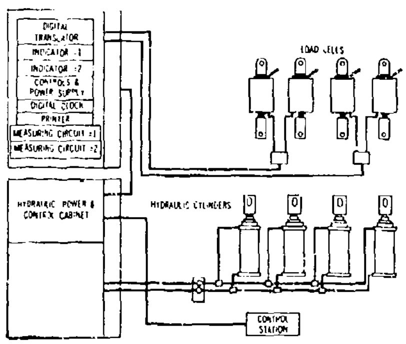

Fig. 4-20 Block Diagram of Field Standard Calibration System

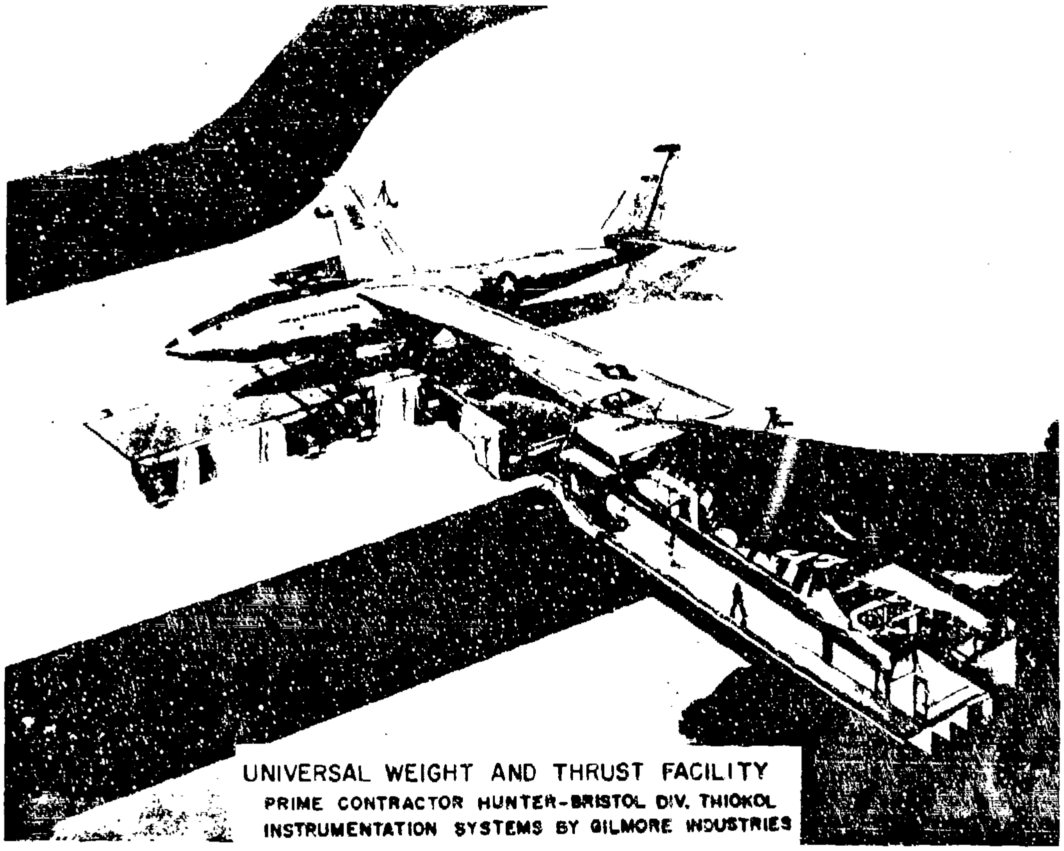

Figure 4-21

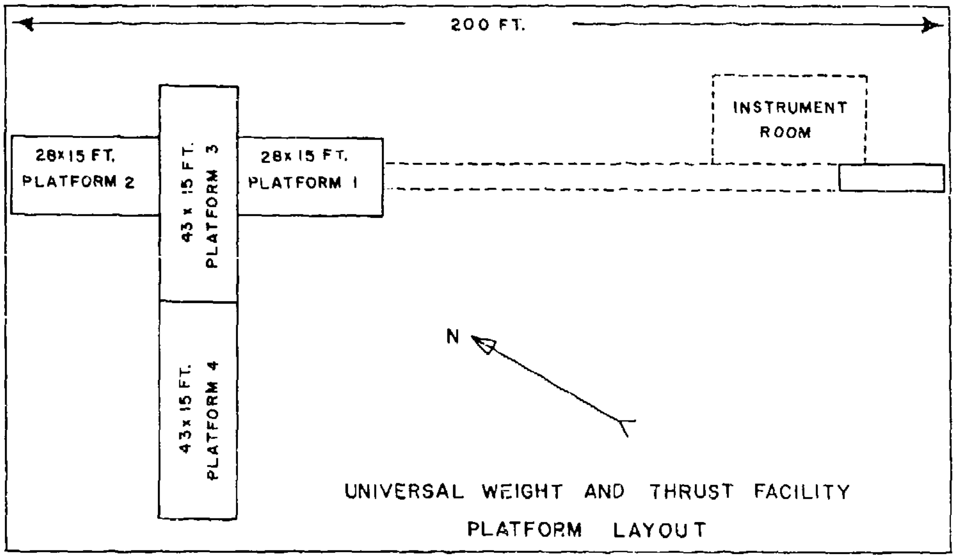

Figure 4-22

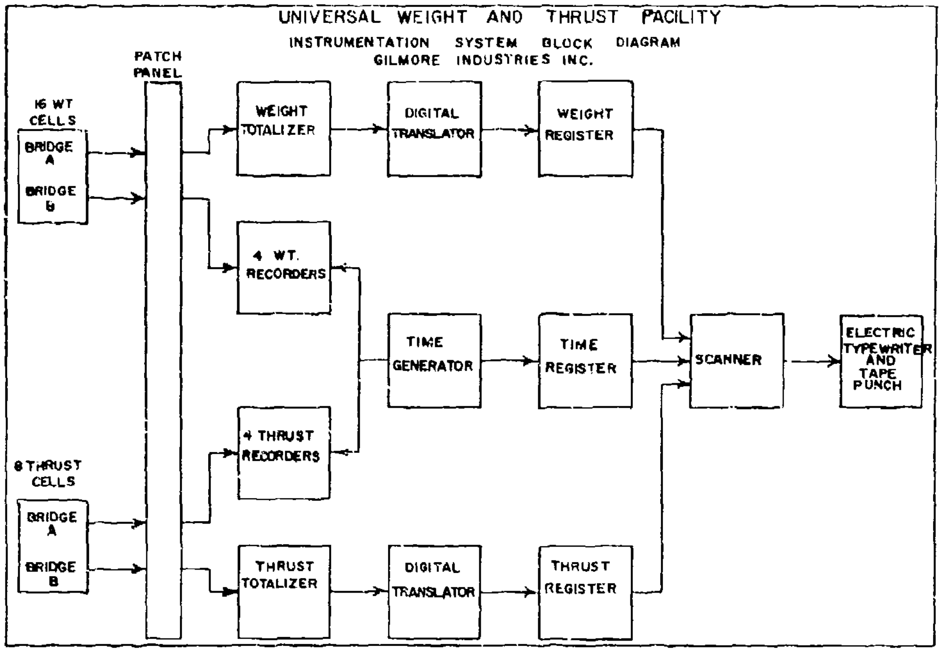

Figure 4-23

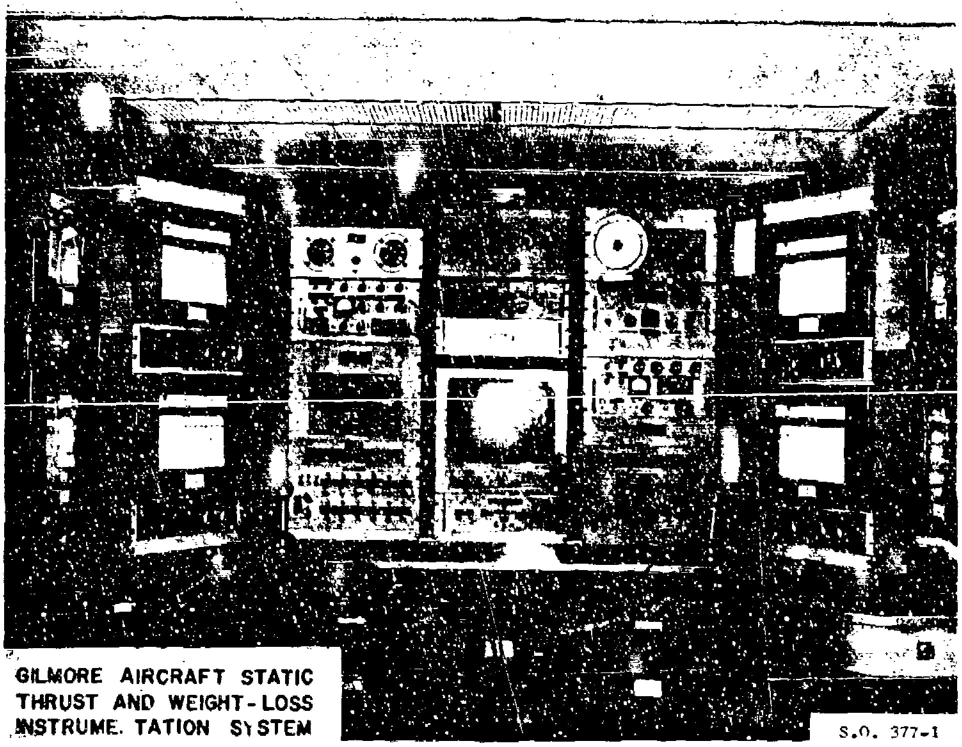

Figure 4-24

hydraulic cylinder to the foundation of the launching pad, pulling down upon the launching frame which holds the missile, and thereby pulling down on the working cells to provide a calibration. The calibration cells furnished with the hydraulic ram are supplied with a separate indicator and are calibrated by the National Bureau of Standards. A field standard calibration system is provided which reads out the load applied on four cells, which in turn is the load being pulled down upon the launcher frame and working cells. This way the calibration cells with the Bureau of Standards record can be compared directly against the working Weight Instrument System, and a direct pound-for-pound calibration made. It should be noted that this calibration can be made with the missile and all of its attachments in place to best simultate actual conditions.

4-16 Testing Gyros At Norden (Ref.312)

Varied test procedures are in practice at different gyro manufacturing facilities, so it is necessary to explain precisely how test results are obtained before one can attach much meaning to such results. The philosophy at Norden is to test the gyros in a manner which most closely approximates an actual operational environment. They have developed a Simultated Platform Test.

This test resembles the frequently user servo test, with one very distinct difference. When a gyro is used in any earth-oriented mode, the local component of earth rate will usually be bucked out by applying a suitable D.C. current to the gyro torquer. But in the normal servo test the torquer is not used. The servo has been modified to include the gyro torquer, by bucking out about 95% of the local component of earth rate with the gryo torquer.

In addition to getting the torquer into the test loop, which gets any torquer errors into the gyro performance characteristics, there is another gain. Since the table now sees only about 5% of earth rate, by amplifying the signal which tells the table motion, also amplifys the error components, and one can now more accurately measure these unwanted outputs from the gyro.

This test is performed by the table to drift through a small known angle and recording table position as a function of time. The table

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312 Technical Bulletin, Norden, Division of United Aircraft Corp. Milford, Connecticut.

is torqued back to its starting position by applying a signal to the gyro torquer, and the run is repeated This is done for a total of ten times in the orientation chosen (Fig.4-26). The standard deviation of the ten runs is short term random drift. The average drift is inserted into an equation along with terms for earth rate, mass unbalances, fixed torque, torquer current and torquer scale factor, etc. The gyro orientation is then changed to that of Fig. 4-27 and the entire procedure is repeated. Next reorientation is to the position of Fig. 4-28 and repeat again. There are now three simultaneous equations and one can readily solve for mass unbalance along the spin axis, mass unbalance along the input axis, and fixed bias.

If the values of mass unbalance fall outside of the specifications, it is a simple matter to go back and rebalance the gyro without draining the fluid or disturbing the seals in any way.

Results of this test for a typical gyro are:

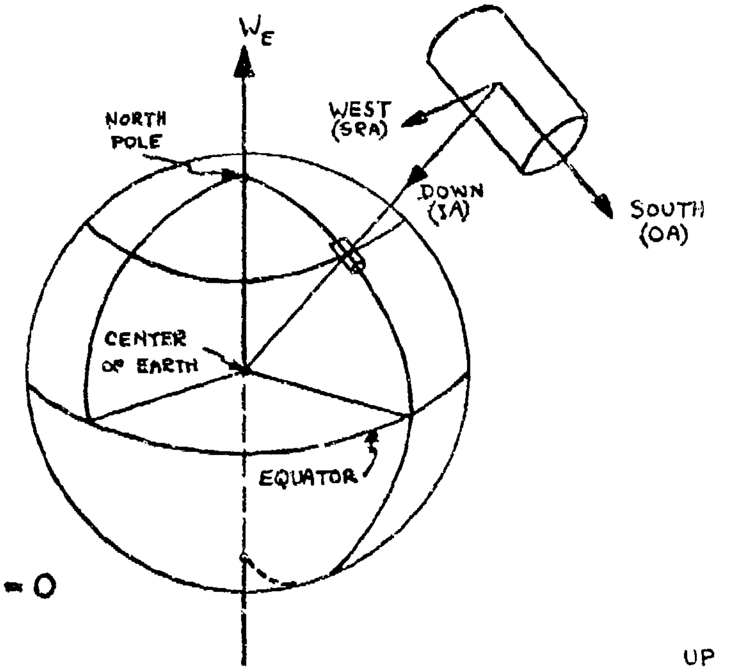
Random drift (output axis horizontal)	0.01°/hr. (one sigma)
Random drift (output axis vertical)	0.005°/hr. (one sigma)
Mass unbalance along spin reference axis	0.10°/hr./g (max.)
Mass unbalance along input axis	0.10°/hr./g (max.)
Fixed bias	0.10°/hr. (max.)

After these thirty runs are completed (ten runs in each of three orientations), the gyro is cooled to room temperature. Upon reheating, the entire procedure is repeated. This cool down and reheat cycle is done five times, and the difference in output from cycle to cycle with no trimming, is day-to-day stability. Typical values for this are:

Day-to-day stability (No trimming)	Std. deviation
Input axis vertical	.1°/hr.
Input axis horizontal	.05°/hr.

A second test which Norden performs is one designed to determine the long term stability of the gyro. This is accomplished by testing the gyro, without trimming, for fifteen continuous hours in the following fashion.

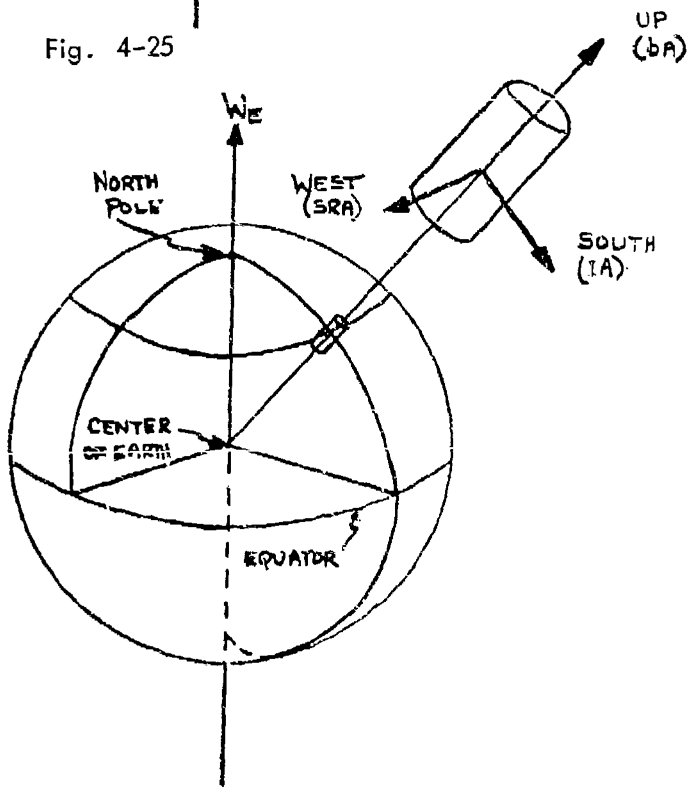
ORIENTATIONS FOR GYRO TEST



SPIN REF. AXIS – WEST
OUTPUT AXIS – SOUTH
INPUT AXIS – DOWN

$$-E_V + W_1 + KC_1 + B + M_{SRA} = 0$$

Fig. 4-25

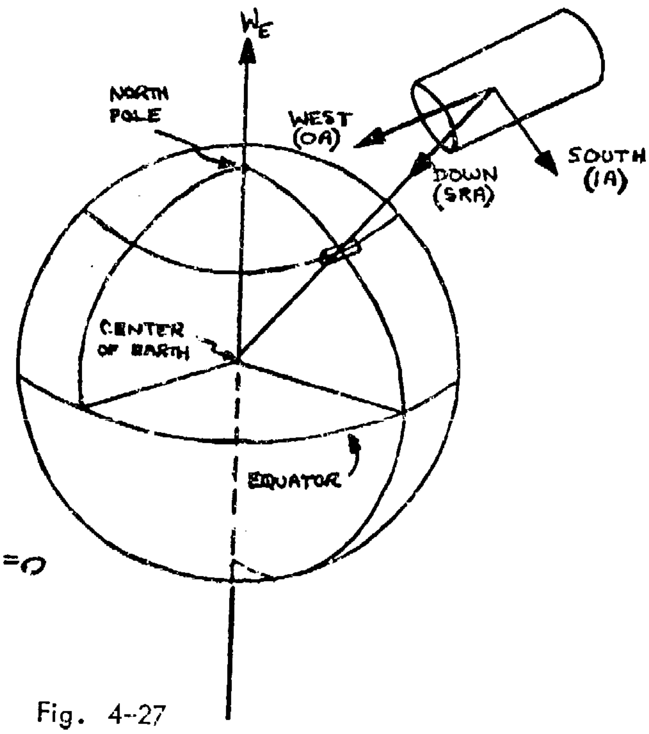


SPIN REF. AXIS – WEST
OUTPUT AXIS – UP
INPUT AXIS – SOUTH

$$-E_H + W_2 + KC_2 + B = 0$$

Fig. 4-26

ORIENTATIONS FOR GYRO TEST - CON'T.



SPIN REF. AXIS - DOWN
OUTPUT AXIS - WEST
INPUT AXIS - SOUTH

$$-E_H + W_3 + KC_3 + B + M_{IA} = 0$$

Fig. 4-27

The test table is oriented to have its axis of rotation parallel to the axis of rotation of the earth. The gyro is mounted on the table with its input axis normal to the table axis, hence normal to the earth's axis. In this orientation the table is rotated at eight times earth rate for fifteen continuous hours, thereby making five complete revolutions. The gyro is not trimmed at all during this test, and the feedback current to the gyro torquer is recorded.

The random component of gyro output is determined by comparing the output from revolution to revolution every 10° of table rotation. Thus, 36 sets of five points each are obtained. The standard deviation of each set is computed. These deviations for a particular gyro are distributed as follows:

Std. Deviation °/hr	Number of Occurrences
.003	1
.01	6
.02	18
.03	8
.04	2
.06	1

Thus, for this gyro, twenty-five of the thrity-six sets have a standard deviation of .02°/hr. or less, and thirty-three of the thirty-six sets have a standard deviation of .03°/hr. or less.

The same test was performed on another gyro, with the exception that data was taken every fifteen degrees of table rotation, resulting in twenty-four sets of five points each. The standard deviations of the twenty-four sets of points for this gyro were distributed as follows:

Std. Deviation	Number of Occurrences
.006	5
.012	9
.018	6
.024	4

4-17 Automatic Testing and Calibration

The rapid advances in all phases of instrumentation involved in missile and space probe programs has led to the extreme necessity of employing automatic checking and calibration of systems. This requirement can fully be understood in considering the multitude of checks performed during "count-down" intervals preceding the launching of a space vehicle or test firing. Each test or check has a related position to every other one and must be performed over and over to keep a running status of operational readiness.

It is the intention here to point out the extra planning and design that must be considered to fulfill an instrumentation system's requirement of not just measuring the performance of a flight but also providing continual pre-flight status checks and simulated calibration signals.

Individual transducers are now being developed such that a calibration command signal well cause the device to deliver a calibrated signal level. Micro-miniaturization, permits incorporating solid state logic switching to shunt or replace a measurement leg of a bridge circuit with a precision calibrated element. Electric charges, precise voltages, known magnetic fields and precise frequency generators or filters can be employed with the sensing element to provide known simultated excitation for test and calibration.

The difficulties facing the instrumentation system engineer are the requirements that each portion pf the system must be available for stage-by-stage operational tests while delivery signals to associated telemetry system sub-systems, control systems and indicating devices without degrading these functions. There are so many complex measurements to be checked and in proper time relation it only becomes feasible through use of fast sampling of test points, with computer type, real time evaluation of the data. Some such arrangement to fit the complexity of the test is what is meant here as automatic test and calibration.

A highly complex launch vehicle such as the proposed Saturn configurations has just a complex a test program for ground static

tests. (Ref.313) See Fig.4-29 for block diagram of instrumentation for static-test tower. A state-of-the-art discussion on test engineering (Ref.314) in the Space/Aeronautics R & D Technical Handbook 1961/62 covers the associated instrumentation problems, approaches toward solution and reported advancements in todays research, environmental and operational testing of space vehicles.

4.18 Instrument Society of America, Aero-Space Standards Division Tests, Calibration and Specifications Guides

"Recommended Practice" reports by various sub-committees of the ISA are available which cover terminology, commonly accepted test procedures, methods of uniform data presentation to render tests easier to perform and more useful and general guides to standardization to promote better communications between transducer users and manufacturers. The following is a list of "Recommended Practices" reports:

RP37.1	Nomenclature and Specification Terminology for Aero-Space Test Transducers with Electrical Output
RP37.2	Specifications and Tests for Piezoelectric Acceleration Transducers for Aero-Space Testing
RP37.3	Specifications and Tests for Strain Gage Pressure Transducers for Aero-Space Testing
RP37.4	Specifications and Tests for Resistive Temperature Sensors for Aero-Space Testing
RP37.5	Specifications and Tests for Strain Gage Acceleration Transducers for Aero-Space Testing
RP37.6	Nomenclature, Specification Terminology, and Qualification, Acceptance Tests, and Calibration Requirements for Potentiometric Pressure Transducers.

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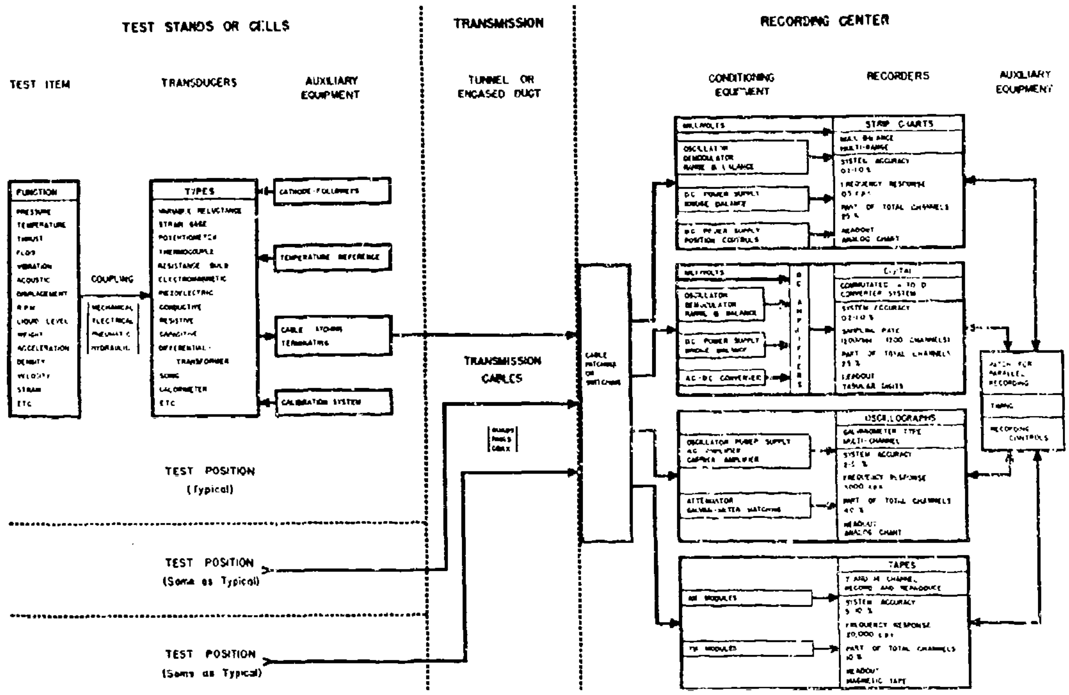
313 Heimburg, K. L., "Saturn Developmental Testing", Astronautics, February 1962.

314 "Test Engineering -- State-of-the-Art", Space/Aeronautics R & D Technical Handbook, 1961-1962.

Control-Systems Plan for Saturn Static-Test Tower



Typical Saturn Static Testing Instrumentation Setup

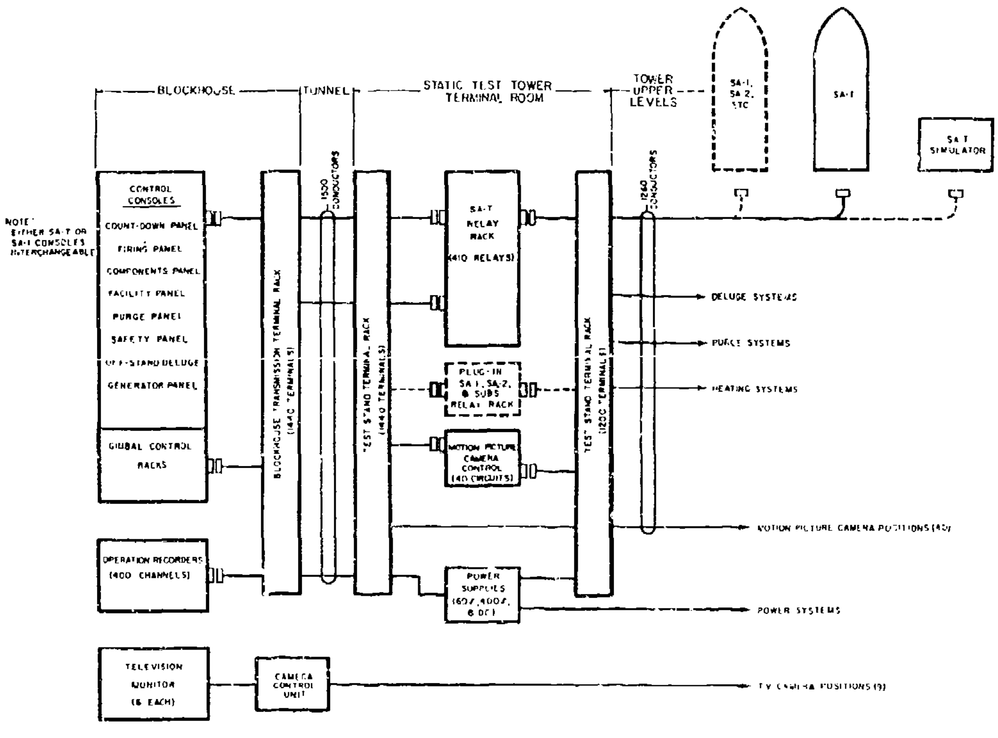


Figure 4-28

SECTION V

TESTING AND CALIBRATION FACILITIES

5-1 INTRODUCTION

This section contains a partial listing of facilities and services which are available to many users of telemetry transducers for testing and calibration. Data used in the preparation of this section was solicited from testing laboratories, government agencies and transducer users.

5-2 MEASUREMENT SERVICES OF THE NATIONAL BUREAU OF STANDARDS, WASHINGTON, D. C.

The major responsibility of the National Bureau of Standards has three main components:

(1) Provision of the central basis within the United States of a complete and consistent system of physical measurements, and co-ordination of that system with the measurement systems of other nations.

(2) Provision of essential services leading to accurate and uniform physical measurement throughout the nation's science, industry, and commerce, and consonant with their advancing requirements.

(3) Provision of data on the properties of matter and materials which are of importance to science, industry, and commerce, and which are not available of sufficient accuracy elsewhere.

The following tables are selected from Summary of Measurement Services of the National Bureau of Standards, prepared by NBS and scheduled for publication early in 1961. The tables have been issued for general information purposes only. With few exceptions, only those services are listed that are performed with sufficient frequency to warrant the establishment of regular fees. In many cases, arrangements can be made to perform calibration of other types or over different ranges or

of higher accuracies than those indicated herein. For convenience, a listing of NBS tables follows:

VIBRATION TRANSDUCERS

Static Methods (Zero Frequency)
Steady State Sinusoidal Method
Special Tests
Small Lightweight Piezoelectric Vibration Transducers

TEMPERATURE

Fixed Points of the International Temperature Scale
Platinum Resistance Thermometers
Thermocouples, Thermocouple Materials, Pyrometer Indicators
Optical Pyrometers, Ribbon Filament Lamps
Liquid-In-Glass Thermometers

PRESSURE AND VACUUM

Calibration Services
Chart of NBS Calibration Accuracies; Ranges of Transmitting Media; Ranges of Some Working Instruments

FORCE MEASUREMENTS: PROVING RINGS AND OTHER ELASTIC LOAD MEASURING DEVICES

HARDNESS

ACOUSTIC MEASUREMENTS

VOLUMETRY, DENSIMETRY

Metal Capacity Standards
Volumetric Glassware
Density
Hydrometers and Thermohydrometers
Fluid Meters
Gas Volume Measuring Instruments
Wind Speed Indicators

RADIATION INSTRUMENTS AND SOURCES

X-Ray and Gamma-Ray Instruments
X-Ray Protective Materials
X-Ray Inspections
Gamma-Ray Measurements of Radioactive Preparations
Neutron Measurements
Radioactivity

RADIOMETRY

PHOTOMETRY AND COLORIMETRY

Standard Incandescent Lamps Furnished by NBS
(Approximately 120 volts)
Standardization of Lamps Submitted
Photometric Instruments and Accessories
Rating of Incandescent Lamps
Reflectometry
Glossimetry
Lovibond Glasses
Other Photometric and Related Standards Supplied
by NBS
Spectrophotometric Standards
Spectrophotometric Measurements
Colorimetry Services

The listed tables are reproduced below. In addition, NBS also offers measurement services in the areas of Mass, Length, Time and Frequency, Electricity, Magnetism, Optical Refraction and Instruments, Photography, Thermal Conductivity, Humidity, Internal Combustion Engine Fuels, Heat Content of Methane Gas, Electroplated Coating Thickness, and Radioactive Labeled Carbohydrates.

Caution: Do not submit equipment for calibration before making preliminary arrangements with the NBS laboratory concerned. Further information on the conditions under which services are available, methods of shipment, fees, etc. can be obtained from the NBS Test Fee Schedules, available on request from the Office of Technical Information, National Bureau of Standards, Washington 25, D. C. Inquiries relating to electrical and magnetic measurements at radio and microwave frequencies and to standard time and frequency broadcasts should be sent to Radio Standards

Division, National Bureau of Standards Boulder Laboratories, Boulder, Colorado. All other inquiries should be addressed to National Bureau of Standards, Washington 25, D. C.

The National Bureau of Standards also distributes standard materials by means of which, in certain measurement areas, owners of measuring equipment can perform their own calibrations. Among the materials of this kind are alloys and ceramics of certified composition to serve as chemical and spectrographic standards; materials of certified purity for standards of pH and freezing point; materials of certified properties for standards of viscosity, humidity, and radioactivity; and a number of industrial standards -- rubbers and rubber-compounding materials, phosphors, color standards, turbidimetric and fineness standards, and others. Information on the technical specifications and purchase procedures for these materials is given in NBS Circular 552, Standard Materials Issued by the National Bureau of Standards, available from Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., price 35 cents.

Primary object: To determine calibration factor of transducer over the amplitude and frequency range for which it will be used. To accomplish this, known inputs are applied along the sensitive axis of the transducer.

Definition of calibration factor: Ratio of transducer output (voltage, record height, amplitude indicated by vibration meter, etc.) to the applied input (displacement, velocity, or acceleration amplitude).

Calibrating inputs: (1) Static (zero frequency) and (2) Steady state sinusoidal.

NOTE: (1) Unless otherwise indicated, the following applies to the calibration of displacement, velocity, and acceleration types of vibration transducers weighing up to 2 pounds.

(2) In the case of piezoelectric acceleration transducers, the preamplifier, the power supply if other than batteries, and the connecting cables should accompany the transducer.

Table 5-1. Static Methods (Zero Frequency)

METHOD	APPLIED ACCELERATIONS	ACCURACY OF APPLIED ACCELERATIONS
Tilting support calibrator, using earth's gravitational field (for transducers with zero transverse response)	$-g$ to $+g$	from 0.004 g near 0 g to 0.0003 g near $\pm g$
Centrifuge calibrator	up to 100 g	1%

Table 5-2. Steady State Sinusoidal Method

METHOD	FREQUENCIES	APPLIED ACCELERATIONS	ACCURACY OF APPLIED ACCELERATION
Electrodynamic calibrator, using reciprocity method	10 to 2,000 cps	up to 10 g	1% for frequencies up to about 900 cps; and 2% for frequencies from 900 to 2,000 cps.

REMARKS: The magnitude and phase angle of the calibration factor are determined unless a transducer is calibrated with a vibration indicator or recorder as a unit. In such cases only the indicated displacements, velocities, and accelerations together with the corresponding applied displacements, velocities, and accelerations are given. Normally, calibration is performed for 3 different accelerations at 10 different frequencies (30 calibration points).

SPECIAL TESTS

In addition to the services listed in Table 5-1 and Table 5-2, a number of special tests are provided. These include the dynamic calibration of transducers weighing more than 2 pounds, and calibrations of small lightweight piezoelectric ceramic transducers over an extended frequency range (see below) or calibrations at higher accelerations. Stroboscopic and fringe-disappearance interferometers are available for some of these measurements.

Table 5-3. Small Lightweight Piezoelectric Vibration Transducers

SERVICE	FREQUENCIES	UNCERTAINTY OF MEASUREMENT
calibration at discrete frequencies	1,000 to 20,000 c/s at low acceleration levels; 500 to 25,000 c/s at high acceleration levels (200 to 12,000 g)	Repeated calibrations on the same transducers agree within 1%. The overall errors of the calibrations are estimated at less than 2%.

Table 5-4. Fixed Points of the International Temperature Scale

FIXED POINT	DEFINED VALUE (°C) (I.T.S. 1948)	REPRODUCIBILITY (°C)
Oxygen: boiling point	-182.970	±0.005
Ice: melting point*	0	±0.0001**
Water: boiling point	100	±0.0005
Sulfur: boiling point	444.600	±0.0015
Silver: freezing point	960.8	±0.2
Gold: freezing point	1063.0	±0.2

* The temperature of equilibrium between ice and air-saturated water at one atmosphere pressure.

** This value applies to the reproducibility of the triple point of water which, in practice, is easier to realize; the temperature of the triple point is taken as 0.0100°C.

Table 5-5. Platinum Resistance Thermometers

TYPE	SERVICE	RANGE	ACCURACY
standard	calibration at oxygen, ice, & steam points	-183° to 630°C	Thermometers of this kind (if they meet certain specifications for design and materials of construction) define the I. T. S. Temperatures at the fixed points are realized with the reproducibilities listed in the table above. However, at temperatures between the fixed points, the defined scale is subject to an additional uncertainty due to variations in the platinum: Between the oxygen and ice pts. this uncertainty is probably less than ±0.002°C; between the ice and steam points it is probably less than ±0.0005°C, between the steam and sulfur points it is probably less than ±0.004°C; and between the sulfur point and 630°C it is probably less than ±0.02°C.
calorimetric	calibration at ice, steam, & intermediate points	-50° to 150°C	
capsule	comparison calibration	12° to 90°K	About ±0.02°C with respect to the thermodynamic temperature scale

Table 5-6. Thermocouples, Thermocouple Materials, Pyrometer Indicators

ITEM	SERVICE	RANGE	CERTIFIED ACCURACY	REMARKS
high-temp thermocouples & thermocouple materials; minimum length 24 in. (exclusive of leads)	comparison of temperatures & corresponding emf's with those of NBS platinum standards	0° to 1,110°C	0.5° (Pt vs Pt-Rh) 1° (base metals)	Results for Pt vs Pt-Rh above 1,100°C are obtained by extrapolation. Base metals not calibrated above 1,100°C.
		1,100° to 1,450°C	1° at 1,100°C to 2° at 1,450°C	
standard Pt vs Pt-Rh thermocouples; minimum length 36" (exclusive of leads), minimum dia. 0.014"	primary calibration at freezing points of Zn, Sb, Ag, & Au and certification of intermediate values.	0° to 1,450°C	0.3° (0° to 1,100°C) to 2° (at 1,450°C); 2 microvolts (about 0.2°C) at fixed points	If thermocouple meets Int. Temp. Scale requirements for standard thermocouples, a quadratic equation fitted at the freezing pts. of Sb, Ag, & Au is furnished.
base-metal thermocouples; minimum length 36" (exclusive of leads)	certification of corresponding values at emf & temperature	-183° to -196°C -110° to 0°C 0° to 500°C	0.1°C (-183° to -196°C) 0.1°C (-110° to 300°C) 0.2°C (above 300°C)	
pyrometer indicators	calibration of scales, meters, & dials (including reference junction compensators) of potentiometers			

Also, the average temperature coefficient of electrical resistance of Pt wire is determined over the interval from 0° to 100°C; samples must have a minimum length of 16" and a resistance of at least 0.1 ohm per foot at the ice point.

Table 5-7. Optical Pyrometers, Ribbon Filament Lamps

ITEM	SERVICE	ACCURACY
optical pyrometers	calibration at specified points in the range, 800° to 4,200°C	The limit of error in these calibrations is usually 4° at 800°C, decreasing to 3° at 1,063°C, and then increasing to 8° at 2,800°C.
ribbon filament lamps	certification of direct current vs brightness temperature (at wavelength of 0.65 microns) for specified points in the range, 800° to 2,300°C	

Table 5-8. Liquid-In-Glass Thermometers

TYPE	SERVICE	RANGE	ACCURACY
Laboratory thermometers	testing at specified temperatures	-110° to 530°C -166° to 1000°F	Well designed liquid-in-glass thermometers are usually certified to 1/10 or 1/5 of the smallest graduation interval, depending on the type of thermometer and the temperature range covered
	testing in liquid air, oxygen, or nitrogen	-183° to -196°C	
calorimetric thermometers	testing at intervals of 2°C or 2.5°F	10° to 50°C	(In laboratory thermometers the smallest graduation intervals are usually between 0.1 and 1 degree C; in a Beckmann thermometer the intervals are usually 0.01 degree C; and in calorimetric instruments the intervals are usually 0.01 or 0.02 degrees C.)
Beckmann thermometers	testing at 1°C intervals by comparison with precision standards	for 5° or 6° scales	
clinical thermometers	tested for compliance with current edition of Commercial Standard for Clinical Thermometers	98°, 102°, and 106°F	Specifications now require that readings should not differ from the precision standard by more than ±0.2° at 98° and 102°F or ±0.3° at 106°F. Test measurements are accurate to 1/5 of a smallest graduation interval (i.e., to ±0.04°F for the usual 0.2° interval).

Table 5-9. Calibration Services

ITEM	RANGE	SERVICE	ACCURACY OF CALIBRATION METHOD
Mercury Barometers	780 mm Hg	Absolute pressure calibration against standard barometer	0.03 mm Hg
Mercury Manometers	2800 mm Hg	Differential calib. against air piston gage or mercury column	0.08 mm Hg
Fortin Barometers	28 to 31 inches of mercury	Comparison with standard barometer at various ambient pressures	0.03 mm Hg
Oil Piston Gages	Up to 60,000 psi	Calibration against oil piston gage	0.01% for area at low pressure 0.01%/10,000 psi for variation of area with pressure
Oil Piston Gages	Up to 200,000 psi	Calibration against oil piston gage	0.05% of pressure range
Precision Pressure Gages (rated accuracies within 1/4% or better)	Up to 60,000 psi	Differential pressure calibration against dead weight piston gage or mercury column	0.02% of pressure range
Precision Aneroid Barometer	Up to 780 mm Hg	Absolute pressure calibration against standard barometer	0.03 mm Hg
Precision Altimeters	Up to 80,000 ft	Absolute pressure calibration against standard barometer	0.03 mm Hg
Air Piston Gages	Up to 500 psi	Calibration against mercury column or air piston gage	0.01% of pressure range
Vacuum gages (In planning stage)	Below 1 mm Hg		

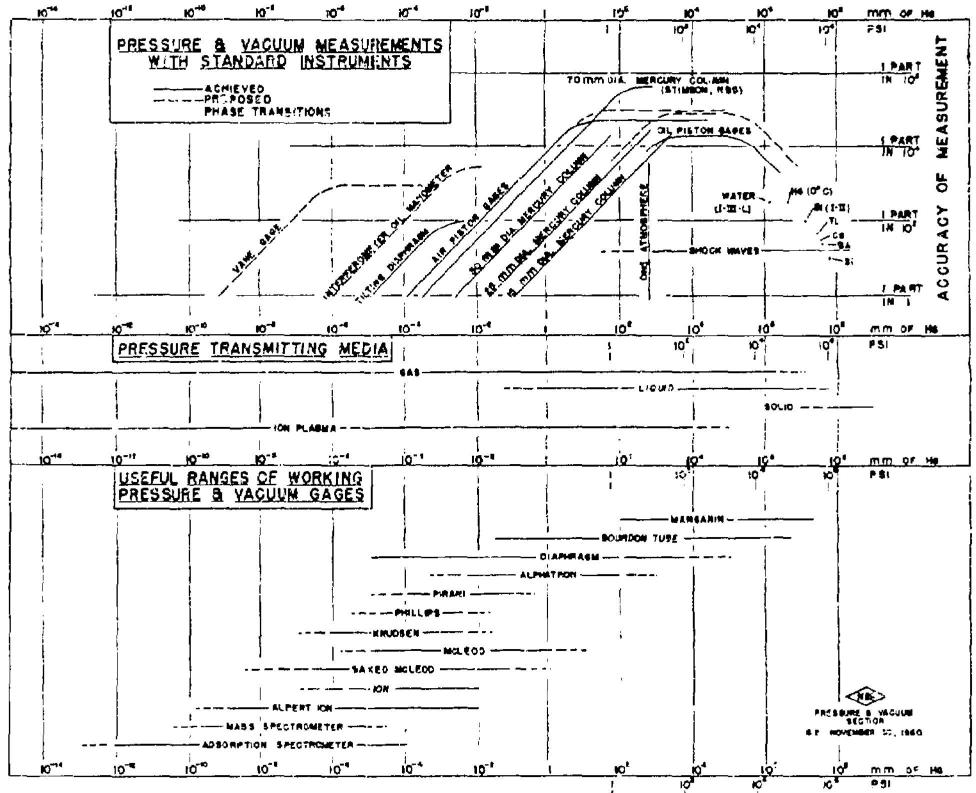


Fig. 5-1. (Top) Accuracies attainable in measurement of pressure and vacuum with standard instruments at the National Bureau of Standards. The accuracies indicated here do not take into account uncertainties in the values of the acceleration of gravity at Washington, D. C., or of the density of mercury. At pressures above 50,000 psi the calibration points are those determined by P. W. Bridgman; accuracies are about 1% at 200,000 psi and about 10% at 2,000,000 psi.

(Center) Useful ranges of pressure transmitting media.

(Bottom) Useful ranges of some working instruments for pressure and vacuum measurements.

FORCE MEASUREMENTS: PROVING RINGS AND OTHER ELASTIC LOAD MEASURING DEVICES

Table 5-10. Force Measurements: Proving Rings and Other Elastic Load Measuring Devices

CAPACITY OF DEVICE	TEST STRESS	ACCURACY	REMARKS
not exceeding 111,000 lb	tension or compression	0.02%	Dead weights.
more than 111,000 lb but not exceeding 1,500,000 lb	compression	0.1%	New dead weight machines up to 1,000,000 lb in tension or compression being designed for accuracies better than 0.01%
more than 1,500,000 lb but not exceeding 3,000,000 lb	compression	0.2%	
more than 3,000,000 lb but not exceeding 10,000,000 lb	compression	0.4%	

HARDNESS

Table 5-11. Hardness

HARDNESS SCALE	SERVICE
Brinell	Determination of Brinell numbers of blocks to be used for calibrating purposes.
Knoop	Measurement of Knoop indenter mounting, included longitudinal edge angle, included transverse angle, and half angles, inspection of edges for nicks, offset at the point, and application of proof load.

Table 5-12. Acoustic Measurements

ITEM	SERVICE	FREQUENCIES c/s	UNCERTAINTY OF MEASUREMENT
various materials (72 square feet of material required)	determination of sound absorption coefficient by reverberation room method	125, 250, 500, 1,000, 2,000, & 4,000	Repeatability varies with frequency. The standard deviation in absorption coefficient is about 0.03 at 125 & 4,000 c/s; & 0.02 at the other frequencies listed.
wall and floor panels (71 by 88 in)	determination of sound transmission loss	125, 175, 250, 350, 500, 700, 1,000, 1,500, 2,000, 3,000 & 4,000	Measurements of the Average STL figure are generally repeatable within ±1db for any particular panel, & within ±2db for nominally identical constructions.
condenser microphones	pressure calibration	50 to 10,000 cps	Standard deviation is approximately 0.06 decibel.
microphones	free-field calibration	50 to 10,000 cps	Standard deviation is approximately 0.17 decibel.
sound level meters	free-field calibration	50 to 10,000 cps	Standard deviation is approximately 0.31 decibel.
fans, sirens, etc.	Measurement of overall sound level generated in normal operation		No advance estimate can be made.
earphones	calibration at specified frequencies: applied voltage response as prescribed in ASA Specification Z24.9-1949	100 to 10,000	The standard error is not more than 0.3 db.
acoustic tiles (1 by 1 ft.)	determination of sound absorption coefficient by impedance tube method	500	Measurements of the sound absorption coefficient are repeatable within ±0.03 units on the same specimen.
pure tone audiometers	calibration		The standard error is not more than 0.3 db for sound level measurements. The overall uncertainty in frequency measurements is no greater than 1 part in 1,000.

Table 5-13. Metal Capacity Standards

INSTRUMENT	SIZE	ACCURACY OF CALIBRATIONS
slicker-plate measures	1 gill or greater, but less than 5 gal or 1/2 bu	1 part in 15,000
	5 gal or 1/2 bu	1 part in 10,000
immersion bottles	1 ft^3	1 part in 25,000
gas bottles	0.1 ft^3	1 part in 2,500
"field" standards (graduated neck measures)	1 to about 500 gal	1 part in 3,500 (less than 5 gal) 1 part in 15,000 (5 gal) 1 part in 5,000 (more than 5 gal)

Table 5-14. Volumetric Glassware

Items submitted are usually calibrated either "to contain" or "to deliver," as indicated in the table below. When an instrument is capable of both kinds of calibration, the accuracy of the calibration "to contain" is generally about twice as good as that of the calibration "to deliver."

INSTRUMENT	CALIBRATED	SIZE	ACCURACY OF CALIBRATIONS
flasks (including spirits measuring flasks)	to contain	10 ml to 1,000 ml	1 part in 2,000 (for 10 ml) to 1 part in 50,000 (for 1,000 ml)
specific gravity flasks	to contain	24 ml	1 part in 5,000
cylindrical graduates	to deliver	10 ml to 1,000 ml	1 part in 1,000 (for 10 ml) to 1 part in 10,000 (for 1,000 ml)
transfer pipettes	to deliver	1 ml to 100 ml	1 part in 1,000 (for 1 ml) to 1 part in 20,000 (for 100 ml)
TC pipettes	to contain	Same sizes as preceding item; same or better accuracy	
burettes (including automatic burettes)	to deliver	5 ml to 50 ml	1 part in 1,000 (for 5 ml) to 1 part in 5,000 (for 50 ml)
microazotometers	to contain	1.5 ml	1 part in 1,500
measuring pipettes	to deliver	1 ml to 25 ml	1 part in 1,000 (for 1 ml) to 1 part in 5,000 (for 25 ml)
dilution pipettes	to contain	about 1 ml	0.5% (ratio)

Table 5-15. Density

SERVICE	ACCURACY OF CALIBRATIONS
For solids: determination of density at room temperature	The accuracy varies with type of material, degree of porosity, shape, mass, degree of care in the observations and calculations, and the refinements of the apparatus used. In general, routine determinations are accurate to 1 part in 10,000.
For liquids: determination of density at specified temperatures from 0° to 70°C, and (if desired) computation of the coefficient of thermal expansion for this temperature range.	The accuracy varies with the stability and type of liquid and with the temperature at which measurements are requested. An accuracy of 1 part in 100,000 is practical in the case of a stable liquid, and this may be improved if the additional time and effort is justified.

Table 5-16. Hydrometers and Thermohydrometers

SERVICE	general inspection, testing at specified points, and marking of hydrometers and hydrometer elements of thermohydrometers
ACCURACY	Corrections are expressed to 1/10 of a scale division; the accuracy of these corrections varies with the instrument design. In general, the precision is such that only in rare instances (depending on the quality of the instrument tested) will the reported correction differ from the true correction by more tha 1/3 of the tolerance listed in NBS Circular 555, Testing of Hydrometers.
REMARK	For calibration of thermometer elements of thermohydrometers, see above under Laboratory Thermometers.

Table 5-17. Fluid Meters

INSTRUMENT	ACCURACY OF CALIBRATIONS
Laboratory wet gas meters: tested with 0.1 ft^3 bottle tested with aspirator	 1 part in 500 1 part in 1,000
dry gas meters	1 part in 400
displacement type meters for liquids	1 part in 400
rate of flow meters: primary calibration calibrated with secondary standards:	 1 part in 400 1 part in 200
orifices and flow nozzles: primary calibration calibrated with secondary standards	 1 part in 300 1 part in 200
water current meters (all types)	1 part in 200

Table 5-18. Gas Volume Measuring Instruments

INSTRUMENT	ACCURACY OF CALIBRATIONS
portable cubic foot standards (Stillman type)	1 part in 1,000
gas meter provers	

Table 5-19. Wind Speed Indicators

SERVICE	calibration of cup, vane, and thermal type anemometers pitot tubes, and Venturi tubes
RANGE	up to about 260 ft/sec
ACCURACY	12% at 1 ft/sec, 2% at 3 ft/sec, 0.5% from 6 to 16 ft/sec, 0.3% above 16 ft/sec

Table 5-20. X-Ray and Gamma-Ray Instruments

Calibration of x-ray dose indicating instruments in international roentgens for lightly, moderately, or heavily filtered x-rays of half-value layers listed in following tables. Calibration of radiation beam within ±2%.

kv cp	approx. inherent filter (mm)	added filter (mm)		approx. half-value layer (mm)	instrument max. range from zero (r)
Lightly Filtered X-rays					
20	2.0 Be	0		0.08 Al	250
20	2.0 Be	.5 Al		0.23 Al	25
30	2.0 Be	.5 Al		0.35 Al	25
50	2.0 Be	1.0 Al		0.87 Al	25
75	2.0 Be	1.5 Al		1.6 Al	25
100	2.0 Be	2.0 Al		2.5 Al	25
Moderately Filtered X-rays					
		Cu	Al		
60	4 Al	0	0	0.09 Cu	25
75	4 Al	0	0	0.11 Cu	100
100	4 Al	0	1.0	0.20 Cu	100
150	4 Al	0.25	1.0	0.66 Cu	100
200	4 Al	.5	1.0	1.2 Cu	100
250	4 Al	1.0	1.0	2.1 Cu	100
250	4 Al	3.2	1.0	3.2 Cu	25

Heavily Filtered X-rays

kv cp	approx. inher. filter (mm)	added filter (mm) Pb	Sn	Cu	Al	approx. effect energy (kev)	Max. dose (r)	Max. range from zero dose rate (r/min)
50	4 Al	0.12	0	0	0	40	1.0	0.1
100	4 Al	.53	0	0	0	70	2.0	0.2
150	4 Al	0	1.5	4.0	0	120	2.0	0.2
200	4 Al	0.7	4.0	0.6	0	170	2.0	0.2
250	4 Al	2.7	1.0	0.6	0	210	2.0	0.2

Dose indicating instruments are also calibrated in international roentgens for cobalt-60 gamma rays. Range: 0.1 to 25 r.

Table 5-21. X-Ray Protective Materials

Determination of opacity of submitted samples
by ionization or radiographic methods.
ACCURACY is generally ±5%.

Table 5-22. X-Ray Inspections

The services in this group are performed only for, or at the request of, other Government agencies. Included in the group are special tests such as: Radiographic inspection of metal objects. Inspection and testing of complete X-ray equipments; X-ray accessories and materials; and radiac equipment.

Table 5-23. Gamma-Ray Measurements of Radioactive Preparation

MATERIALS	usually radium or encapsulated cobalt-60	REMARKS: Radium is calibrated in terms of milligrams of radium content measured relative to the National Radium Standard. Cobalt-60 is calibrated in terms of dose rate (milliroentgens per hr at 1 m), based on comparison with derived standards of cobalt. See also below, under RADIOACTIVITY.
RANGE	0.5 to 250 mg of radium; 0.5 to 200 milliroentgens per hour at 1 meter of cobalt-60	
ACCURACY	±0.7% for radium; ±3% for cobalt-60	

Table 5-24. Neutron Measurements

SERVICE	ACCURACY
Neutron sources: Determination of the neutron emission rate of submitted unknown source by intercomparison with the national standard in $MnSO_4$ bath or graphite column.	±3 to 5% depending on the source
Neutron instruments: Calibration of sets of thermal neutron dosimeters	*Disturbances in the flux are introduced depending on the nature of the instrument being calibrated so that the uncertainty in the flux is typically ±3 to 5%. The overall calibration accuracy depends on the particular instrument being calibrated.*
Neutron irradiation of foils: Activation of sets of foils in the NBS standard thermal neutron flux.	About ±5%

Table 5-25. Radioactivity

Calibration of gamma-emitting and alpha-emitting samples. Gamma-emitting samples must conform to the physical, chemical, and activity-level specifications for measurement in the NBS ionization chamber. (See the NBS Test Fee Schedules, section 204.901, for further details.)

SERVICE	ACCURACY
20 to 300 micrograms of radium: calibration in terms of micrograms of radium content measured relative to the National Radium Standard (gamma emission)	±1/2 to 3%
Gamma emission can be measured in chemically stable solutions of the following nuclides: sodium-22, sodium-24, potassium-42, scandium-46 iron-59, cobalt-60, zinc-65, strontium-85, niobium-95 iodine-131, cesium-137-barium-137, tantalum-182, gold-198, mercury-203	±2%
Calibration of alpha emission rate of sources submitted	±2%

TABLE 5-26. Radiometry

ITEM SUBMITTED	SERVICE
standards of total radiation	Lamps seasoned and calibrated for intensity of radiant energy. RANGE is from 40 to 80 microwatts per cm^2 at 2 meters. ACCURACY is about 1%.
standards of spectral radiation	Lamp seasoned and calibrated for spectral radiance, from 0.25 to 0.75 micron and from 0.5 to 2.6 microns. ACCURACY: 3 to 5%
germicidal or sterilamp	Measurement of radiant flux of 2537 A. ACCURACY: about 2%
radiant energy meter	Calibration of meter for energy of wavelength 2537 A produced by lamp.
eye-protective glasses	Test for compliance with safety code, for transmission of ultraviolet, visible and total radiation; test for luminous transmittance by comparison with standard filters; measurement of percent ultraviolet transmittance at regular intervals or selected points in the spectrum.
laminated safety glass	Determination of effect of exposure to ultraviolet radiant energy.

The ACCURACIES attainable in the following photometric and colorimetric measurements are generally of the order of 1%.

Table 5-27. Standard Incandescent Lamps Furnished by NBS
(Approximately 120 volts)

TYPE	STOCK SIZES (WATTS)	STANDARDIZED PROPERTY
clear, screw base	100, 250, 500	luminous intensity (candles)
inside-frosted, medium bipost base	100, [illegible], 500	
clear or inside-frosted screw base	100, [illegible], 500	luminous flux (lumens)

Table 5-28. Standardization of Lamps Submitted

TYPE	WATTAGE	SERVICE	REMARKS
incandescent, approx. 120 volts medium, mogul, screw, or medium bipost base	100 to 1,000	determination of horizontal candles in specified direction	If necessary, lamps are seasoned before being standardized.
	10 to 1,000	determination of luminous flux	Routine methods available for lamps of the indicated type and wattage; for other types and for wattages below or above the indicated values, special equipment may be needed.
white or daylight fluorescent lamps		determination of luminous flux	
mercury vapor lamps		determination of luminous flux	

Table 5-29. Photometric Instruments and Accessories

ITEM	SERVICE
portable photometers and illuminometers	calibration at specified values in range from 1 to 1,000 footcandles, or equivalent luminance
luminance standards	calibration at specified values, monochromatic, between 1 and 10,000 footlamberts
filters, neutral or colored	determination of luminous transmittance

Table 5-30. Rating of Incandescent Lamps

Routine photometric tests of the type made initially on lamps to be life-tested. Purpose is to afford a quick check of the photometric values assigned to lamps by lamp life-test laboratories. Wattages ordinarily up to 1,000 watts. Accuracies are of the order of 2%.

Table 5-31. Reflectometry Standards Issued

Non-selective standards, calibrated for CIE tristimulus values, X, Y, Z; 4-1/4 in. square with 1/4 in., 90° fold at each edge; in colors ranging from white through gray to black.
Chromatic reflectance standards, calibrated for CIE tristimulus values, X, Y, Z; 3 by 5 in. plaques in colors commonly called white, bath green, kitchen green, orchid, ivory, maize, bath blue, delphinium blue, royal blue, and red.
S Chromatic reflectance standards, calibrated for CIE tristimulus values, X, Y, Z; 4-1/4 in. square with 1/4 in., 90° fold at each edge; in colors commonly called safety red, aviation orange, school bus chrome, safety yellow, safety green, and safety blue.
SAMPLES OR STANDARDS SUBMITTED FOR CALIBRATION
Determination of directional reflectance relative to MgO or other standard, with angles and apertures restricted to available instruments, for incandescent-lamp or artificial-daylight illumination, or for a spectral region determined by a source-filter-receptor combination.

Table 5-32. Glossimetry

The following standards can be furnished generally within 5 units of any specified glass value.

MATERIAL	USE	APERTURES	DIMENSIONS
Polished, ground, sand-blasted, or acid-etched glass, or glazed ceramic tile, as required to obtain desired gloss values and to approximate reflected light-flux distributions of various commercial materials frequently measured for gloss.	For checking the accuracy of glossmeters designed to measure specular gloss at 20°, 45°, 60°, 75°, & 85°.	As prescribed by established methods of test, such as those of ASTM, TAPPI, and PEI.	Usually 4-1/4 in. square, except 65° standards which are 3 by 9 inches.

Table 5-33. Lovibond Glasses

Lovibond red glasses are measured to determine the numeral on the additive (N') scale established (by Priest and Gibson's adjustment of set BS 9940) at this Bureau in 1927, the value given being the effective value when the submitted red glass is used in combination with a 35-yellow glass.

Table 5-34. Other *Photometric* and *Related Standards Supplied* by NBS

TYPE	DESCRIPTION
Capacity standards	Diffusing glass rectangles, 5 by 12 cm; opacity determined by contrast-ratio method (TAPPI test method T425m-36); opacity range 0.50 to 0.96.
Haze standards	Used for checking accuracy of hazemeters designed to measure haze according to ASTM Method D1003. Standards are 2-in. squares, about 1/4 in. thick, of hazy cellulose acetate sheeting laminated between glass. Nominal values are 1, 5, 15, and 25% haze.

Table 5-35. Spectrophotometric Standards

STANDARDS ISSUED	DESCRIPTION	REPORT INCLUDES
Spectral transmittance standards for checking photometric scale of spectrophotometer	Polished glass disks, 2 to 3 mm thick and 30 mm in diam; designated as cobalt blue, copper green, carbon yellow, & selenium orange	(1) Values of transmittance at 25 C at certain wavelengths from 390 to 750 mμ; (2) estimated uncertainty of each value, (3) effect of temperature change on transmittance at each wavelength. On request, transmittances also determined at wavelengths from 365 to 390 mμ and from 750 to 1,000 mμ at temperature of 25 °C.
Didymium glass standards for checking wavelength calibration of GE recording spectrophotometers	Corning 5120 glass, 2 by 2 in., 3.0 mm thick, polished	Table of wavelengths of minimum transmittance. Measurements made in range 400 to 750 mμ with slits equivalent to about 10 mμ of spectrum; and in range 730 to 1,080 mμ with 20 mμ slits.
Working standards of spectral directional reflectance for use on GE recording spectrophotometer with 6-degree from perpendicular irradiation & diffuse reception	Vitrolite glass, 4 by 4 in., 5/16 in. thick	Table of spectral directional reflectances relative to freshly prepared MgO at every 10 mμ for one or more of the following ranges and conditions: (1) 400 to 750 mμ, specular component both included and excluded, 10 mμ slits; (2) 730 to 1,080 mμ, specular component both included and excluded, 20 mμ slits.
Working standards of spectral directional reflectance for use on Beckman quartz spectrophotometer (Model DU) with nearly perpen. irradiation & approx 45° circular reception	White structural Vitrolite glass, 1-1/2 by 2 in., 5/16 in. thick	Tables of spectral directional reflectance relative to freshly prepared MgO at every 10 mμ, for various ranges between 350 and 1,200 mμ.
STANDARDS SUBMITTED FOR CALIBRATION		
Spectral transmittance standards for checking photometric scale of spectrophotometer	Must be in good optical condition	Transmittance values at specified wavelengths from 365 to 1,000 mμ at room temperature. Measurements can be made at other specified temperatures if specimen is a glass disk 29.7 ± 0.2 mm in diam.

Table 5-36. Spectrophotometric Measurements

The following measurement services are provided primarily for informational purposes, and samples so tested should not be accepted as NBS-certified standards.

PROPERTIES MEASURED	WAVELENGTHS (mμ)	SLITS (mμ)	SPECTROPHOTOMETER
Spectral transmittance	210 to 1,000		Beckman DU
Spectral directional reflectance relative to MgO, normal irradiation & 45° circular reception	254 to 1,000		Beckman DU
Spectral transmittance or transmittancy curves, including 100% and zero calibration curves and didymium glass curve for checking wavelength calibration	400 to 1,080	10 or 20	GE recording
Spectral directional reflectance curves, including Vitrolite calibration curve for correcting values relative to fresh MgO as 100%, zero curve, and didymium glass curve for checking wavelength calibration	400 to 1,080	10 or 20	GE recording

Table 5-37. Colorimetry Services

Computation of chromaticity coordinates and luminous reflectance or transmittance from spectrophotometric data for certain specified light sources.
Determination of the Munsell notation or book notation of a specimen from its daylight reflectance and chromaticity coordinates.
Determination of conformity in chromaticity of sample to standard, both illuminated normally by artificial daylight or by incandescent lamp, with chromaticity expressed in terms of chromaticity coordinates on fundamental colorimetric coordinate system.
Determination of color temperature of 120-volt screw-base incandescent lamp; voltage for specified color temperature, and current for neighboring voltage to check permanence.
Determination of approximate color temperature of lamps to be calibrated as photometric standards.
500-watt lamp issued, for which color temperatures at specified voltages have been determined, or for which equation is determined giving color temperature from 2,000 to 2,854°K.
Colored filters, for use either to define chromaticity limits in specifications or to calibrate meters used in the measurement of color and luminance of instrument panels, are issued.

5-3 ENVIRONMENTAL BRANCH, ASFEV

AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE,
OHIO

a. Dynamics Section, ASFEVD

(1) Vibration

The facility for dynamic evaluation contains approximately 20 vibration machines to cover a broad range of conditions. This includes the following unique equipment for vibration testing and evaluation:

(a) Low Frequency - High Amplitude Machine

Freq. Range:	0.5 to 30 cps
Displacement:	9 inches
Load Capacity:	1000 pounds

(b) Medium Frequency Electromagnetic Shaker

Freq. Range:	5 to 500 cps
Force Output:	12,500 pounds
Load Capacity:	500 pounds (2000 pounds by use of special suspension system)

(c) High Frequency Electromagnetic Shaker

Freq. Range:	5 to 2000 cps with capability for simulating random or complex wave vibration
Load Capacity:	200 pounds

(2) Acceleration

A centrifuge with the following characteristics is available for testing and evaluation of transducers and other equipment:

Acceleration:	30 g with full load; 50 g for short runs and limited loads
Load Capacity:	16,000 pounds
Arm Radius:	Approximately 6 feet

This unit is especially suited for combining other environments with acceleration.

(3) Combined Environments

(a) Large Centrifuge

A system is available for performing tests and evaluations of equipment operating under any environmental combination consisting of steady state acceler ion, vibration, and ambient temperature. In addition, the system has the capability of simulating altitude concurrently with any combination of the above, with the exception of low temperature environments.

The following ranges of environments may be applied to the equipment under investigation:

Steady State Acceleration (S. S. A):	0 - 50 g
Vibration:	5 to 2000 cps, sinusoidal or random; ± 20 g with 20-pound load; 600 pounds force; may be applied in a direction which is parallel to the S. S. A. or perpendicular to the S. S. A.
Ambient Temp:	250°F to 500°F
Altitude:	800 to 100,000 feet (not in combination with low temperature)

(b) Chamber

A 6' x 7' x 6' chamber with the following capabilities is available for testing and evaluation of equipment under combined environments:

Altitude:	0 to 75, 000 feet
Temperature:	-70° to + 500°F
	-70° to + 700°F (Ram Air)
Dew Point:	-70° to + 700°F
Air Press. Flow, Steady State:	38.2 psia -225 lb/min
Air Press. Flow, Blow Down:	700 lb/min (20 sec)

(4) Shock

Several machines are available for producing a large variety of shock pulses. Load capacities for these machines range from 50 to 400 pounds.

(5) Acoustic Energy

The Dynamics Section (WWFEVD) is responsible for a large acoustic test facility which is located at the plant of Bolt, Beranek and Newman, Incorporated, Cambridge, Massachusetts. This facility consists of a very large exponential horn with a driver mechanism. It is located in an enclosure whose concrete walls are tectum insulated. The enclosure is 54 feet in length and 27 feet in width. The driver mechanism is capable of producing 22,000 watts of pure tone or narrow-band noise energy to provide an intensity of 174 db above 10^{-16} watts/centimeter^2 at the equipment being tested.

b. Space and Atmospheric Deterioration Section, WWFEVS

The following facilities are available for simulation of weapons systems environmental profile requirements. In many instances, they can be modified to meet special requirements.

(1) Combined Environmental Facility

Size:	3 ft. wide x 3 ft. long x 4 ft. high
Temp. Range:	-100°f to +200°F
Altitude:	55,000 ft.

This facility permits combination of temperature - altitude - time patterns which can simulate the flight profile of altitude or space conditions within the vehicle.

(2) Space (High Altitude) Chamber, Building 45A

Size:	4 ft. dia. x 5 ft. long
Altitude:	450,000 ft.

This facility can be utilized for simulation of space conditions for evaluation of equipment components and subsystems. It includes instrumentation for accurate recording of altitude and capability of maintaining conditions once achieved.

(3) Low-High Temperature (Ground Support) Facility, Building 25A

Size:	25 ft. wide x 75 ft. long x 25 ft. high; facility can be separated into two rooms having 35 and 40 ft. lengths
Temp. Range:	-80°F to +160°F (in either or both rooms)

This facility can be utilized for evaluation of complete systems under temperature extremes including large items and systems of ground support equipment.

(4) Systems Altitude - Temperature Facility, Building 22

Size:	18 ft. dia. x 17 ft. high - height can be increased by adding 6 ft. rings
Temp. Range:	-90°F to +175°F
Altitude:	Ground level to 165,000 ft.

This facility is supplemented by a 15-tone overhead monorail hoist. Large items of equipment may be evaluated under altitude and temperature conditions. In its present condition, this facility can accommodate certain space vehicle payloads and, with moderate modification, be capable of accommodating larger space systems.

(5) Explosion - Proof Facilities, Buildings 45A and 47A

Size:	Large facility - 7 ft. dia. x 8 ft. long Medium facility - 3 ft. dia. x 5 ft. long

Temp. Range:	Room temp. to 350°F
Altitude:	Ground level to 100,000 ft.

Various combinations of fuel/gas mixtures (propulsions system products) may be simulated in these facilities to determine ignition characteristics of explosive or flame producing mixtures and ignition capability of electrical arc and high temperature equipment components.

(6) Solar Radiation Facility, Building 45

This facility simulates the sun's solar radiation at the earth's equator. Special lamps and filters are used to simulate the sun's spectrum.

Available information indicates feasibility of simulation lights of solar radiation in space with only a moderate modification of existing facilities and additional equipment.

(7) Atmospheric Environment Facilities

Humidity:	50% to 100% RH at temperatures up to 200°F
Salt Fog:	5% to 20% salt solution
Sand and Dust:	0.1 to 0.5 grams/cu. ft.
Fungus:	5 types of cultures
Rain:	1 to 6 inches per hour
Arid:	Relative humidity of 5% at temperatures up to 600°F

(8) Ram Air Temperature - Altitude Facility

Ambient Air Temp:	-80°F to +100°F
Cooling Ram Air Temp:	-80°F to +100°F
Ram Air Static Press. Range:	5 to 35 inches of water
Altitude:	80,000 ft.

This facility is capable of testing generators, alternators and other rotating or nonrotating equipment when simulated cooling air is required through the equipment.

5-4 SINGLE INTEGRATED U.S. AIR FORCE CALIBRATION SYSTEM 2802D INERTIAL GUIDANCE AND CALIBRATION GROUP (MAAMA) HEATH ANNEX NEWARK, OHIO

The U.S. Air Force has a single integrated calibration system to support all Air Force activities. Operation of this system is depicted in Figure 5-2. Standards are maintained at Air Materiel Areas (AMA), Air Force Depots (AFD) and designated Air Force Bases (AFB). The 2802D IG & C Gp (MAAMA), as the central calibration agency for the Air Force, calibrates or assures calibration of and certifies AMA and AFD Standards. The Air Materiel Areas, in turn, calibrate and certify Air Force Base Standards. In addition to calibrating Air Force Base Standards, the Air Materiel Areas calibrate and certify precision measurement equipment utilized in their own laboratories. Air Force Bases, which have standards, calibrate precision measuring equipment for assigned and tenant units.

AMA and AFD Electrical and Electronics Standards are calibrated by the National Bureau of Standards at Boulder, Colorado. A detachment of Air Force personnel equipped with AMA and AFD Electrical and Electronic Standards is stationed at the Boulder Laboratories of the National Bureau of Standards. The standards with which the detachment is equipped are calibrated by the National Bureau of Standards and hand carried by detachment personnel to AMA's and AFD's once a year where they are exchanged for AMA and AFD standards which are due for recertification. During visits to the AMA's and AFD's, detachment personnel provide technical assistance on calibration of working standards.

AMA and AFD Electro-Mechanical Standards are calibrated by the USAF Calibration Division. The Electro-Mechanical transfer standards are hand carried to the AMA's and AFD's by Division personnel once a year where they are used to calibrate and certify AMA and AFD standards. The transfer standards are hand carried back to USAF Laboratories where they are checked to assure that they have not changed in accuracy while in transit.

AMA and AFD Dimensional Standards are calibrated by the USAF Calibration Division. The Dimensional Standards are hand carried to the AMA's and AFD's once a year where they are exchanged for AMA and AFD Dimensional Standards which are due for recertification.

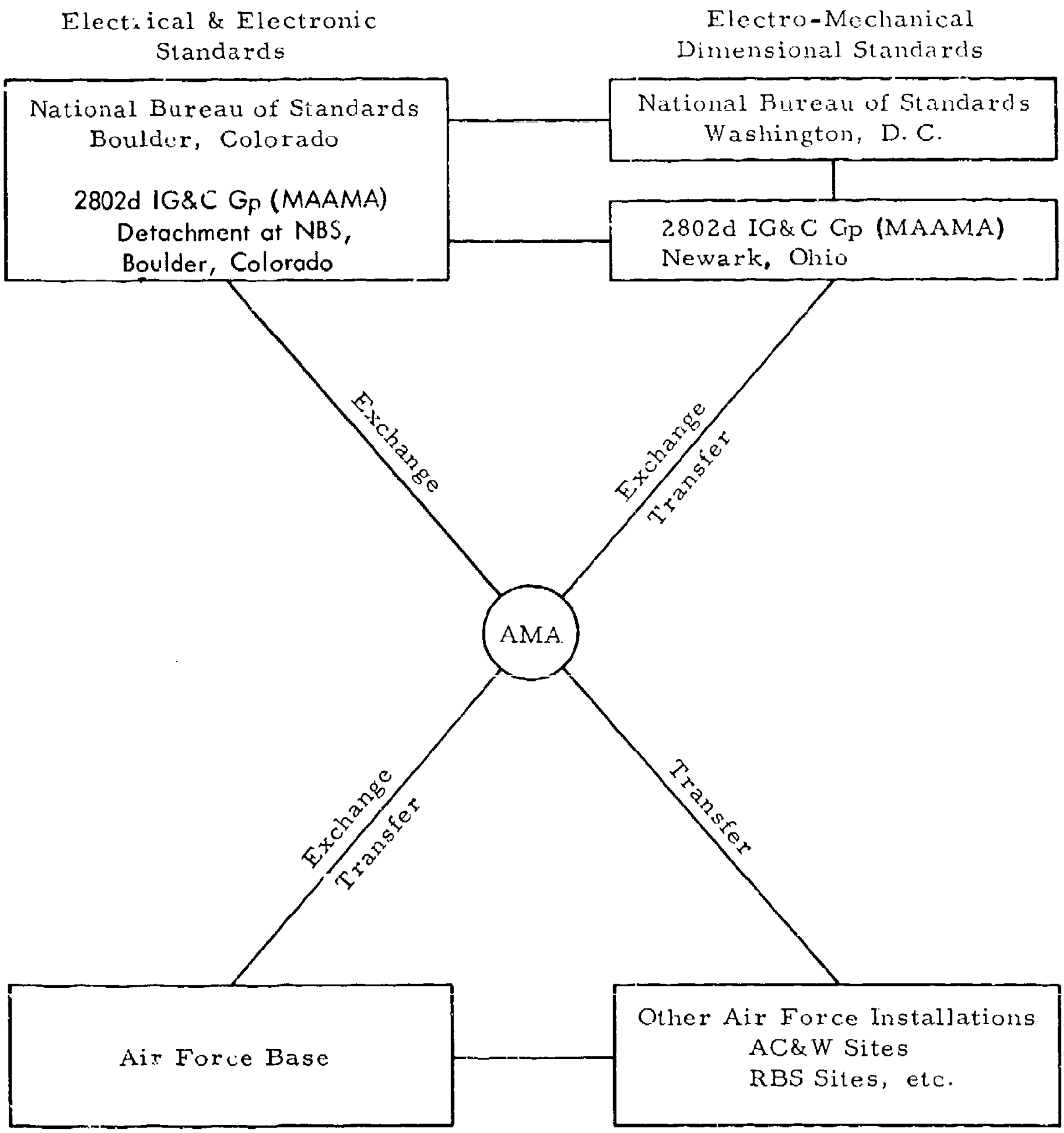


Fig. 5-2. Operation of the Single Integrated USAF Calibration System

Air Force base standards are calibrated and certified by the Air Materiel Areas. The AMA's maintain exchange sets of base standards which are calibrated in the AMA Laboratories and certified using the AMA standards. The AMA's establish schedules and hand carry exchange standards to the base PMEL. While at the base PMEL, AMA personnel calibrate and certify base standards, which by size, etc. cannot be exchanged, and provide technical assistance to base PMEL personnel in repair, calibration and certification of precision measurement equipment.

Activities authorized to possess AMA or AFD electrical, microwave, electro-mechanical and dimensional standards are listed in Table 5-38. Activities authorized Base electrical, microwave, electro-mechanical and dimensional standards are listed in Table 5-39.

Table 5-38. Activities Authorized to Possess AMA or AFD Standards

Zone of Interior	Zone of Interior & Overseas
MAAMA, Olmsted AFB, Pa	Eglin AFB, Fla
MOAMA, Brookley AFB, Ala	Vandenberg AFB, Cal
OCAMA, Tinker AFB, Okla	Det #18, SMAMA (Pacific Mobile Depot) Tachikawa AB, Japan
OOAMA, Hill AFB, Utah	USAFE (Contr. Opr. Depot in France)
SAAMA, Kelly AFB, Tex	Pinetree East (Canada)
SBAMA, Norton AFB, Cal	Pinetree West (Canada)
SMAMA, McClellan AFB, Cal	Elmendorf AFB, Alaska
WRAMA, Robins AFB, Ga	
Patrick AFB, Fla	

Table 5-39. Activities Authorized to Possess Base Standards

BASES	BASES
Albrook AFB, Canal Zone Altus AFB, Okla Amarillo AFB, Tex Anderson AFB, Guam Andrews AFB, Md Arnold Engineering Development Center, Tullahoma, Tenn Aviano AB, Italy	Duluth Municipal Airport, Minn Dyess AFB, Tex
Barksdate AFB, La Beale AFB, Calif Bergstrom AFB, Tex Biggs AFB, Tex Bitburg AB, Germany Blytheville AFB, Ark Brize Norton AFB, England Bunker Hill AFB, Ind	Edwards AFB, Calif Eglin AFB, Fla Ellsworth AFB, S. D. England AFB, La Ent AFB, Colo Ernest Harmon AFB, Newfoundland Evreus/Fauville AB, France
Camp New Amsterdam, Netherlands Cannon AFB, N. Mex Carswell AFB, Tex Castle AFB, Calif Chanute AFB, Ill. Charleston AFB, S. C. Chaumont AFB, France Chennault AFB, La Clark AFB, P. I. Clinton-Sherman AFB, Okla Columbus AFB, Miss Craig AFB, Ala	Fairchild AFB, Wash Forbes AFB, Kansas Francis E. Warren AFB, Wyo
Davis-Monthan AFB, Ariz Donaldson AFB, S. C. Dover AFB, Del Dow AFB, Maine	George AFB, Calif Glasgow AFB, Mont Goose AFB, Goose Bay, Labrador Grand Forks AFB, N. D.
	Hahn AB, Germany Hamilton AFB, Calif Hanscom Field, Bedford, Mass Hickam AFB, Hawaii Holloman AFB, N. Mex Homestead AFB, Fla Hunter AFB, Ga
	Incirlik AB, Turkey Itazuke AB, Japan
	James Connally AFB, Tex
	K. I. Sawyer Airport, Mich Kadena AB, Okinawa

Table 5-39. Activities Authorized to Posses Base Standards (continuation)

BASES	BASES
Keesler AFB, Gulfport, Miss	Naha AB, Okinawa
Kindley AFB, Bermuda	Nellis AFB, Nev
Kingsley AFB, Oregon	Niagara Falls Muni Apt, N. Y.
Kinchloe AFB, Mich	Nouasseur AB, Morrocco
Kirtland AFB, N. Mex	
Kuramursel AFB, Turkey	Offutt AFB, Neb
	Osan AB, Korea
Lajes Field, Azores	Otis AFB, Mass
Lakenheath AFB, England	Oxnard AFB, Calif
Langley AFB, Va	
Laon AB, France	Paine AFB, Wash
Laredo AFB, Tex	Patrick AFB, Fla
Larson AFB, Wash	Pease AFB, N. H.
Laughlin AFB, Tex	Perrin AFB, Tex
Lincoln AFB, Neb	Plattsburg AFB, N. Y.
Little Rock AFB, Ark	Pope AFB, N. C.
Lockbourne AFB, Ohio	Portland Muni Apt, Ore
Loring AFB, Maine	
Lowry AFB, Colo	RAF, Alconbury, England
Luke AFB, Ariz	RAF Bentwaters, England
	RAF Sculthorpe, England
MacDill AFB, Fla	RAF Wethersfield, England
Malmstrom AFB, Mont	Ramey AFB, Puerto Rico
March AFB, Calif	Ramstein AB, Germany
Mather AFB, Calif	Randolph AFB, Tex
McChord AFB, Wash	Reese AFB, Tex
McConnel AFB, Kansas	Rhein/Main AB, Germany
McCoy AFB, Fla	Richards-Gebaur AFB, Mo
McGuire AFB, N. J.	
Minot AF Station, N. D.	Schilling AFB, Kansas
Misawa AB, Japan	Scott AFB, Ill
Moody AFB, Ga	Selfridge AFB, Mich
Moutain Home AFB, Idaho	Seinbach AB, Germany
Myrtle Beach AFB, S. C.	Sewart AFB, Tenn

Table 5-39. Activities Authroized to Possess Base Standards (continuation)

BASES
Seymour Johnson AFB, N. C.
Shaw AFB, S. C.
Sheppard AFB, Tex
Spangdahlem AB, Germany
Spokane Intl Apt, Spokane, Wash
Stead AFB, Nev
Stewart AFB, N. Y.
Suffolk Co. AFB, L. I., N. Y.
Thule Air Base, Greenland
Torrejon AFB, Spain
Toul AFB, France
Travis AFB, Calif
Traux Fld, Wis
Turner AFB, Ga
Tyndall AFB, Fla
Vance AFB, Okla
Vandenberg AFB, Calif
Walker AFB, N. Mex
Webb AFB, Tex
Westover AFB, Mass
Wheelus AB, Libya
Whiteman AFB, Mo
Wiesbaden AB, Germany
Williams AFB, Ariz
Wurtsmith AFB, Mich
Wright-Patterson AFB, Ohio
Yokota AB, Japan

5-5 WESTERN PRIMARY STANDARDS LABORATORY - U.S. NAVY POMONA, CALIFORNIA

Table 5-40. Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Acceleration	20 - 1000 cps		Bausch & Lomb Microscope
Flow	0.014 - 416 gpm	Repeatability ±0.2%	NBS referenced Flow Stand
Force	50 - 100,000 lbs	0.2%	NBS Certified Proving Rings
Pressure	50-20,000 psi in oil	1 part in 10,000	NBS Certified Piston Gage
	3-150 psi in air	1 part in 10,000	NBS Certified Piston Gage
	1 micron vacuum		Reference McLeod Gage
Temperature	-190°C to +200°C	0.01°C	NBS Cert. Plat. Res. Therm.
	0 C to 1500°C	0.5°C	NBS Cert. Thermo-couples
Torque	6000 in lbs.		Dead weight calibrated Torque Tester
Vibration	See acceleration		

Table 5-41. Electrical/Electronic Measurement Accuracy Capabilities

VARIABLE	RANGE	ACCURACY	STANDARD
Voltage DC	Standard Cells 1 - 11,000 μv 11,000 - 111,000 μv 0.1 - 1000 v 1.0 k - 50 k v	±1 microvolt ±(0.01% + 0.02 μv) ±(0.01% + 0.1 μv) ±0.005% ±0.1%	Saturated Std. Cells & Comparator Thermofree Potentiometer Thermofree Potentiometer Voltage Divider & Std. Cell Voltage Divider & Potentiometer
Voltage AC	10 - 100 mv (50 - 10k cps) 100 mv - 8 v (50 - 10k cps) 8 - 1200 v (20 - 20k cps) 1.2k - 6.9 kv (60 cps) 6.9k - 30 kv (60 cps)	±0.15% ±0.06% ±0.05% ±0.45% ±1.0%	Transfer Voltammeter & Ratio Xfmr Transfer Voltammeter & Ratio Xfmr Transfer Voltammeter & Volt Box Extension Dynamometer & Voltage Xfmr Electrostatic Voltmeter
Current DC	0.001 - 0.1 μa 0.1 μa - 100 ma 0.1 - 30 a 30 - 600 a	±0.03% ±0.02% ±0.03% ±0.05%	Standard Resistor & Potentiometer Standard Resistor & Potentiometer Standard Resistor & Potentiometer Potentiometer & Calibrated Shunt
Current AC	50 ma - 5.0 a (20 - 20k cps) 5.0 - 150 a (20 - 500 cps)	±0.05% ±0.15%	Transfer Voltammeter Transfer Voltammeter & Current Xfmr
Power DC	1 mw - 3 kw 3 - 225 kw	±0.04% ±0.1%	Potentiometer & Standard Resistor Potentiometer, Shunt & Volt Box
Power AC	0.4 - 1500 w (20 - 20k cps) 1500 w - 45 kw (50 - 500 cps) 45 - 180 kw (60 cps)	±0.1% for unity P.F. ±0.2% for unity P.F. ±0.35%	Transfer Voltammeter Transfer Voltammeter & Current Xfmr Transfer Voltammeter, Current Xfmr, Volt Box Extension
Resistance Standards	0.001, 0.01, 0.1 ohm 1.0 ohm 10, 20, 50, 100, 200, 500, 1k, 2k, 10k ohms 100k ohms	±0.001% ±0.0005% ±0.001% ±0.002%	Standard Resistor & Precision Wenner Bridge Thomas 1-ohm Std. & Precision Wenner Bridge Standard Resistor & Precision Wenner Bridge Standard Resistor & Precision Wenner Bridge
Intermediate Values	10 - 50 μohms 50 μohms - 1 ohm 1 - 100,000 ohms 0.1 - 10 megohms	±0.02 μohms ±0.04% ±0.015% ±0.05%	Kelvin Bridge Kelvin Bridge Wheatstone Bridge Std. Resistor & Wenner Potentiometer
Inductance Standards	Decimal Multiples of 1, 2, 3, or 5 from 100 - 1000 μh (1k cps) and 2 - 100 mh (1k cps) 0.2, 0.4, 1 h, 2 h, 5 h (50 - 1000 cps)	±0.5 μh ±0.03% ±0.03%	Std. Inductor & Comparison Bridge Std. Inductor & Comparison Bridge Std. Inductor & Comparison Bridge
Intermediate Values	0.1 μh - 1000 mh (60 - 10k cps) 1 - 10 h (1000 cps) 100 - 1000 h (1000 cps)	±(0.2% + 0.1 μh) ±0.3% ±0.6%	Std. Inductor & Comparison Bridge Std. Inductor & Maxwell Bridge Std. Inductor & Maxwell Bridge

(continued)

Table 5-41. Electrical/Electronic Measurement Accuracy Capabilities (continuation)

Capacitance Standards	Decimal Multiples of 1, 2, 3 or 4 from 10 $\mu\mu f$ to 0.1 μf (1000 cps)	$\pm(0.1\% + 0.1\ \mu\mu f)$	Std. Capacitor & Mod. Schering Bridge
Intermediate Values	0 - 10 $\mu\mu f$ (30 - 300k cps)	$\pm 0.01\ \mu\mu f$	Std. Capacitor & Mod. Schering Bridge
	10 - 40 $\mu\mu f$ (30 - 300k cps)	$\pm 0.04\ \mu\mu f$	Std. Capacitor & Mod. Schering Bridge
	40 - 100 $\mu\mu f$ (30 - 300k cps)	$\pm 0.1\%$	Std. Capacitor & Mod. Schering Bridge
	100 - 200 $\mu\mu f$ (30 - 300k cps)	$\pm 0.2\ \mu\mu f$	Std. Capacitor & Mod. Schering Bridge
	200 - 1000 $\mu\mu f$ (30 - 300k cps)	$\pm 0.1\%$	Std. Capacitor & Mod. Schering Bridge
	0.001 - 0.1 μf (1k cps)	$\pm 0.15\%$	Std. Capacitor & Mod. Schering Bridge
	0.1 - 100 μf (50 - 20k cps)	$\pm 0.3\%$	Capacitance Comparison Bridge
	100 - 1000 μf (50 - 20k cps)	$\pm 0.6\%$	Capacitance Comparison Bridge

Table 5-42. Physical Measurements, Accuracy Capabilities, Including Metrology, Hardness, Vibration

VARIABLE	RANGE	ACCURACY	STANDARD
Length			
Gage Blocks	0.01 - 4.0 in	5 μin	Certified Gage Blocks & Comparator
	5.0 - 20.0 in	1 μin per inch of length	Certified Gage Blocks & Comparator
Linear	20 - 160 in	$\pm$(25 μin + 1 μin per inch length)	Gage Blocks & Long Length Meas. Machine
Angular			
Full Circle	0° - 360°	$\pm$3 seconds arc	Calibrated 30° Polygon
Small Angles	to 10 minutes	$\pm$0.2 seconds arc	Auto-collimator
Flatness			
Gage Blocks	All Sizes	$\pm$2 μin	Monochromatic Light with Optical Flats
Optical Surface	to 8-in diameter	$\pm$2 μin	Monochromatic Light with Optical Flats
Surface Plates	All Sizes	$\pm$5 min per foot of max linear dimension	Auto-collimator
Surface Finish			
RMS	0 - 1000 μin	$\pm$10%	Profilometer
CLA	0 - 200 μin	$\pm$10%	Talysurf
Hardness			
Micro & Macro Knoop & Vickers	Full Range	Impression Length $\pm$0.001mm	Certified Test Blocks
Rockwell	B&C Scale	$\pm$1.5 scale numbers	Certified Test Blocks
Screw Thread			
Lead	to 8 in O.D. (2)	20 μin	Lead Measuring Machine & Length Standard
Pitch Diam	to 12 in O.D. (2)	25 μin	Certified Set of Thread Wires
(2) all threads - internal, external, straight and tapered.			
Vibration			
Amplitude	0.001 - 0.4 inch (20 - 2000 cps)	$\pm$(1% + .001") to 0.1 in	Microscope with calibrated reticle
Acceleration	to 25 g's max	$\pm$4% to 10 g's	Calibrated Velocity pickup
Frequency	20 - 2000 cps	$\pm$0.02%	Freq. Standard & Comparison Oscilloscope
Sound	20 - 150 dbm (20 - 20k cps)	$\pm$0.4 db	Standard Microphone - Pressure Calib.
	70 - 110 dbm (10 - 650 cps)	$\pm$0.2 db	Piston phone

Table 5-43. Temperature Measurement Accuracy Capabilities

VARIABLE	RANGE	ACCURACY	STANDARD
Temperature Fixed Points	+0.010°C abs.	±0.0005°C	Triple Pt. Cell
	+100.000°C abs.	±0.001°C	Steam Bath
	+231.88°C	±0.01°C	Freezing Pt. of Tin
	+327.40°C	±0.01°C	Freezing Pt. of Lead
	+419.50°C	±0.01°C	Freezing Pt. of Zinc
	+660.0°C	±0.2°C	Freezing Pt. of Aluminum
	+960.8°C	±0.2°C	Freezing Pt. of Silver
	+1083.3°C	±0.2°C	Freezing Pt. of Copper
Intermediate points	−183°C — +630°C	±0.02°C	Resistance Thermometer
	+630°C — +1100°C	±0.5°C	Thermocouples
	+1100°C — +1450°C	±1°C — ±2°C	Thermocouples

Table 5-44. Pressure Measurements Accuracy Capabilities

PRESSURE (Abs)	ACCURACY	INSTRUMENT
0.005 micron - 1.0 mm Hg	±10%	McLeod Gauge
0 - 30 in of water	±0.004 in H_2O	Water Manometer
0.3 - 50 psi	±0.01 psi	Dead-weight tester
50 - 500 psi	±0.125 psi	Dead-weight tester
500 - 10,000 psi	±0.1%	Dead-weight tester

5-7 SANDIA CORPORATION

a. Livermore, California

Table 5-45 Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Acceleration, Linear	1-800 g's, infinite variation	±1%	Aircraft Tachometer
Acceleration, Vibration (Sinusiodal)	50-5000 cps: 100 g's peak 5.8K cps: 20,000 g's peak (1 oz. max. wt.)	±2% ±2%	NBS Optical Displacement Follower
Acceleration, Shock	30,000 g's peak, approx. half-sine pulse, 300 usec. duration, or equivalent	±5%, Repeatability	Quartz Crystal
Displacement	0-2 inches	±0.01%	Micrometer
Force	0-600,000 pounds	±0.005%	NBS
Frequency	$0-10^9$ cps	1 part in 10^7 million	NBS
Pressure	Dry Nitrogen gas, 0-10,000 psig	±1%	Dead Weight Tester
Temperature	-130°F to +850°F	±0.25%	Mv Pot.
Voltage, DC	0-750V 1,000 - 10,000V	±0.05% ±1%	Volt Boxes & Pot.
Voltage, AC	0-1, 500V	±0.1%	Thermal Converter Volt Box & Pot.
Resistance	10^{-4} - 5 x 10^{12} ohms	±1%	Kelvin & Wheatstone Bridges

Table 5-45 Testing and Calibration Facilities (contd)

Variable	Range	Accuracy	Standard
Capacitance	100 uufd - 1.1 ufd	±1%	Capacitance Bridge
Humidity	5% to 95% between +35°F and +175°F	±10%	Saturated Salt Solutions
Altitude	Ambient to 130,000 ft.	±1mm Hg	Hass Manometer
Sand - Dust	Air velocity: 100 fpm to 500 fpm and 2,300 fpm to 3,000 fpm Air temperature: +70°F to +160°F Particle size: Constant, 0.1 to 0.5 grams per cubic foot		
Vacuum	1×10^{-6} mm of Hg	±10%	McCleod Gage
Thermal Conductivity	Temp. Range: -65°F to +1400°F Conductivity Range: 0.1 to 10 BTU/F^2/HR/°F/IN	±1%	NBS
High Temp. Dilatometer	±0.10 inches	±1%	Mv Pot. & Quartz Rod

The above testing facilities are available for TWG use when the necessary AEC "Q" clearance is obtained.

b. SANDIA CORPORATION, FIELD TEST
TRANSDUCER COMPONENT CONTROL SECTION, 7213-3
SANDIA BASE
ALBUQUERQUE, NEW MEXICO

Table 5-46. Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Linear Acceleration	1 to 1000 g	0.5%	Revolution counter on spin table
Displacement	0 to 1"	0.001"	Micrometer
Pressure	1 micron to 5 mm Hg	±10% of reading	McCleod gage
	1 mm Hg to 75 mm Hg	±0.05 mm Hg	Oil manometer
	1 mm Hg to 800 mm Hg	±0.2 mm Hg	Mercury manometer
	0.1 to 31 in. Hg	±0.03 in. Hg	Dead weight tester
	0 to 60 psia	±0.12 psi	Dead weight tester
	0 to 300 psia	±0.6 psi	Dead weight tester
	0 to 2000 psia	±4.00 psi	Dead weight tester
Temperature	-90°F to +2000°F	±1.0°F	Triple point of water and thermocouples
Vibration	1 to 100 g	3% 10 to 30 cps	Optical and frequency
	5 to 20 g	3% 100 to 1000 cps	Optical and frequency
	20 to 100 g	10% 1000 to 2000 cps	Optical and frequency

Table 5-47. Instrumentation Capability List

Variable	Range	Accuracy	Standard
Temperature	-100°F to 1800°F	2% $\pm$ 0.5°F	Thermocouple, Thermistor
Pressure	10^{-4} to 10^{5} psi	1%	Manometer, dead weight tester
Acoustic Noise	30 to 15 k cps 160 db spl	5%	ASA Standard Microphone
Vibration	10 to 15 k cps at 0 to 100 g's, 6 oz. maximum	1.5%	Optical micrometer and quartz crystal frequency standard
Linear Acceleration	0 to 1000 g's, 2500 g-lbs. max.	1%	Optical micrometer and quartz crystal frequency standard
Mass	10^{-5} - 10^{3} grams	0.1% $\pm$ 0.01 mg	Analytic balance
Force	5 x 10^{4} lbs.	1.0%	Force tester with lab. standard proving rings
Moment of Inertia	10^{-4} - 50 (slug ft^2)	0.5%	Standardized test specimens
Angular Acceleration	± 2 - 3K rad/sec^2	2%	Gauge and torsional pendulum
Voltage, DC	10^{-6} - 10^{3} volts	0.1%	Standard cells, potentiometer and precision supply
Voltage, AC	10^{-3} - 10^{3} volts	0.2%	Transfer standards and ratio transformer
Resistance	10^{-2} - 10^{7} ohms	0.05%	Standard resistor and bridge

(continued)

Table 5-47. Instrumentation Capability List (continuation)

Variable	Range	Accuracy	Standard
Current, DC	10^{-8} - 10^{2} amps	0.1%	Potentiometer and standard resistor
Current, AC	10^{-3} - 10^{2} amps	0.2%	Transfer standards and ratio transformer
Inductance	10^{-5} - 10^{2} henries	1%	Standard inductor and bridge
Capacitance	10^{-12} - 10^{3} micro-farads	0.5%	Standard capacitor and bridge
Frequency	1 - 10^{8} cps		Quartz crystal frequency standard
Rotational velocity	0 - 5 x 10^{4} rpm	1%	Stroboscope and electronic counter
Rotational displacement	10^{-4} degrees	1%	Index head and mirror
Angle of attack	± 15 degrees	0.25°	Precision potentiometer, index head and height gauge
Strain	0 - 4 x 10 micro in/in	± 10 micro inch	Strain gauge instruments
Sideslip	± 15 degrees	0.25°	Precision potentiometer, index head and height gauge
Power, DC	10^{-3} - 10^{3} watts	0.5%	Standard resistor and potentiometer
Power, AC	1 - 10^{3} watts	0.5%	Transfer standard and transformer

5-9 U.S. NAVAL ORDNANCE TEST STATION
CHINA LAKE, CALIFORNIA

Table 5-48. Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Vibration	0-30 g	±4%	Endevco Model 2215 Accelerometer
Pressure	0.3-3000 psi	±0.2%	CEC Precision Pressure Standard
Force	0-1000 g	±0.5%	Genisco Model A-903 Centrifuge

5-10 ELECTRICAL TESTING LABORATORIES, INCORPORATED
2 EAST END AVENUE
NEW YORK 21, NEW YORK

Table 5-49. Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Light Intensity	10^{-6} to 10^{6} cp	1/2% - center range 10% - extremes	NBS Cal. Lamps
Radiant Heat Flux	5 to 5 x 10^{6} Microwatts/ cm^2	2% - center range 10% - extremes	NBS Cal. Lamps

Table 5-50. Testing and Calibration Facilities

Measurand	Range	Accuracy	Standard
Pressure	0-31 " of Hg	±0.0005" of Hg	Mercurial Barometer
Pressure	Sea level-105" of Hg	±0.0005" of Hg	Mercurial Manometer
Load (tension and compression)	0-20,000	±1%	Baldwin-Lima-Hamilton Corp. Calibration
Load (tension and compression)	0-120,000 lb	±1%	Baldwin-Lima-Hamilton Corp. Calibration
Vibration	Freq. range is 2 cps to 2,000 cps. Force output is 600 lb. at 30 to 2,000 cps. Max. stroke - 1". 1 lb. load up to 25 g ; 37 lb load up to 10 g	±5%	MB Vibration Meter
Vibration	Freq. range is 5-500 cps. Transmitted force is 2,500 lb. No load up to 26.5 g; 100 lb. load up to 15 g	±5%	MB Vibration Meter

(continued)

Table 5-50. Testing and Calibration Facilities (continuation)

Measurand	Range	Accuracy	Standard
Vibration	Freq. range is 10-5,000 cps. Peak force at 1,000 cps is 22 lb. Stroke is 1/2"	±0.02 g	Endevco accelerometer calibrated by the Bureau of Standards
Vibration	Freq. range is 10-3,000 cps. Peak force at 500 cps is 50 lb. Stroke is 1/2"	±0.02 g	Endevco accelerometer calibrated by the Bureau of Standards
Shock	Duration of shock pulse is 10±1 milliseconds. Max. g is 400 g	±5%	Compounded calibrated equipment
Constant Acceleration	Max. acceleration is 15 g; capacity is 300 lb.	±5%	Compounded calibrated equipment
Altitude Temperature Humidity	Sea level to 80,000 feet -70°C to 80°C In excess of 95%	±100 ft. ±2°C ±5%	Mercurial Manometer Brown Recorder Micromax - Leeds and Northrup calibration
Altitude Temperature	Sea level to 60,000 feet -55°C to 80°C	±100 ft. ±2°C	Mercurial Manometer Brown Recorder
Altitude	Sea level to 150,000 feet	±100 ft.	Mercurial Manometer (A McLeod gauge is used over 90,000 ft.)
Temperature	-70°C to 500°C	±2°C	Brown Recorder

5-12 NAVAL AIR TEST CENTER, FLIGHT TEST DIVISION, U. S. NAVAL AIR STATION, PATUXENT RIVER, MARYLAND

Table 5-51. Common Instrumentation Measurements and Calibration Standards

Variable Measurand	Range	Accuracy	Standard
Acceleration	0 - ±20 g	Under 1/2 of 1%	Pendulum; vibration table; centrifuge
Attitude (gyro)	±180°	Under 1/2 of 1%	Calibrated tilt table
Angular Rate (gyro)	720°/sec	Under 1%	Pendulum or centrifuge
Pressure	0 - 300 psi	Under 1/2 of 1%	Lab manometer or dead weight tester
Revolutions/min.	0 - 20,000 rpm	Under 1/2 of 1%	Lab tachometer bench with electronic counter
Altitude	0 - 80,000 ft.	Under 1%	Lab barometer
Airspeed	0 - 1000 kt	Under 1%	Lab manometer
Fuel Flow	0 - 120,000 lb/hr	Under 1/2 of 1%	Lab fuel flow bench with electronic counter
Force measurements on large members (such as aircraft arresting hooks)	0 - 120,000 lb.	Under 1%	Lab weights or hydraulic tension machine
Vibration	0 - 200 cps	Under 1%	magnetic vibration table

5-13 ROTOTEST LABORATORIES INCORPORATED
2803 Los Flores Boulevard
Lynwood, California

Table 5-52 Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Acceleration	0-100 g	1/2%	Precision Centrifuge
Mass	6-200 gms 0-4.5 lbs	±.01 mg ±.01 oz	Analytic Beam Bal. Bal. Scale
Force	0-5,000 lbs 0-100 lbs	2% 1/2%	Deadweight Calibrated Tensile Tester
Voltage DC	0-500 v	.05%	Differential VTVM (nulling device)
Voltage AC	0-500 v.a.c.	.2%	Differential VTVM (nulling device)
	30 cps to 5 kc	.1%	Transfer Standards
Temperature	-60 - +5 °C -5 to +202 °C +198 - +360 °C	±.2°C ±.1°C ±.5°C	Thermometer Standard
Resistance	1 ohm - 10^6 ohms	.012%	Standard Resistors .01% with .001% voltage divider
	10^{-6} - 1 ohm	.5%	Kelvin Bridge
Linear Displacement	0 - 6 inches	.001 inch	Mm, Machinist Table
Angular Displacement		30 sec	Angular dividing head optically calibrated to 5 sec accuracy

Table 5-52 Testing and Calibration Facilities (contd)

Variable	Range	Accuracy	Standard
Voltage Ratio Measurements			
AC	50 cps - 3 kc	.001%	Prec. ratio trans
	3 kc - 10 kc	.01%	Prec. ratio trans
DC		±.00001	Prec. v divider
Capacitance	100 uuf - 1.15 uf	.1%	Standard Capacitance Bridge
Inductance	0 - 1,111 hy	1%	Incremental Inductance Bridge
	100 uhy - 10 hy	.2%	Hay Owen Bridge Circuit
Time) Frequency)		Stability of Standards	WWVH or Digital Counter
Pressure			Ion Gauge, McLeod Gauge
	10^{-6} mm Hg to 10^{4} psi	1 micron	Manometer, dead-weight tester
		1 mm	
		.2%	
		.1%	Bourdon type press. gauge
Temperature	Fluid baths 0-200°C		Lab. Standard Thermometers
	-100 - +600°F Component chamber	±1/2°F	
	-100 - +1500°F	±2°F	
Vibration	5 - 2,000 cps	±5%	Crystal accel.
	10,000 force lb.		Ling 275
	5,000 force lb.		MB C25H
	750 force lb.		MB C5
	600 force lb.		Calidyne 44A
	50 force lb.		

Table 5-52 Testing and Calibration Facilities (contd)

Variable	Range	Accuracy	Standard
Shock	Half sine wave Saw tooth Square wave	±10%	Crystal accel.
Acoustics	37.5 - 10 kc, 153 db 8 inches x 8 inches cross-sectional area of test chamber		Capacitive microphone VU broad band & octave analyzers
Altitude	0 - 700,000 feet (10^{-6} mm Hg)		Ion Gauge
		1 micron	McLeod Gauge
		±1 mm	Standard Manometer

Table 5-53. Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Temperature	12°K to 900°K	±0.02°C to 0.0005°C	Platinum resistance thermometer
Temperature	273°K to 1700°K	±0.3°C to 2°C	Platinum vs plat. Rhod. thermocouple
Temperature	1300 to 3000°K	±3°C to 8°C	Optical pyrometer
Light Intensity	0 to 700 candles at 1 ft.		Tungsten Lamp
Pressure	1×10^{-8} to 1×10^{-4} Tor.	20% to 30%	Ionization gage
Pressure	1×10^{-4} to 1 Tor.	2.5%	McLeod
Pressure	1 to 100 tor.	0.1%	Butylphthalate manometer
Pressure	800 tor.	5×10^{-2} tor.	Mercury barometer
Pressure	0.5 to 50 psi	0.02% of indicated	Air piston gage
Pressure	50 to 500 psi	0.1%	Air piston gage
Pressure	500 to 10,000 psi	0.1%	Hydraulic piston gage
Pressure	10,000 to 100,000 psi	2%	High pressure hydraulic system

(continued)

Table 5-53. Testing and Calibration Facilities (continuation)

Variable	Range	Accuracy	Standard
Force	0 to 500 lbs.	0.01%	Dead weights
Force	0 to 60,000 lbs.	0.05%	SG load system
Force	60,000 to 100,000	0.50%	Hydraulic loading machine
Mass	0 to 75 lbs.	2 mg to 0.50 gm	St'd weights & balance
Flow	0 to 250 CFH	1%	Gas meter
Flow	0 to 100 CFM	0.5%	Flowmeter
Flow	0 to 50 GPM	1%	Liquid weight system
Static Accel-eration	0 to 1000 g	0.25 to 1%	Centrifuge
Static Angular Displacement	0 to 360°	3 sec. of arc	Dividing head
Dynamic Angular Displacement	±30° 0.25 to 90 cps	0.01°	Pendulum
Linear Dis-placement	11"	2×10^{-6} in/in to 4×10^{-6} in/in	Gage blocks
Shock:	1.5 to 6M sec 0 to 500 g	10%	Drop test equipment
Static Angular	0 to 1200°/sec.	0.1%	Rate Table
Vibration	6 to 2000 cps 0 to 40 g	2.0%	Electro dynamic calibrator

JET PROPULSION LABORATORY
California Institute of Technology
Engineering Facilities Division and Hydraulics Lab
Pasadena, California

Table 5-54 Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Press., pneumatic or hydraulic (Oil)	6 psi to 2428 psi 30 to 12,000 psi	±.01% of press. at greater than 1/2 FS .05% min.	Prec. dead weight piston gage with pneumatic isolator
Press., pneumatic (automatic calib.)	0 - 25, 0 - 100, 0 -300, 0 - 500 0 - 1000 psi (10 steps/range)	.05% of FS range	Calib. by prec. piston gage
Pressures	0 - 1/2 psia	0.05% of full scale	Oil manometer using std hydrometer for oil density check
	0 - 80 cm Hg	0.1% of full scale	Mercury manometer with temp. corrected scale
	0 - 9000 psi	0.025% of full scale	Oil filled dead weight tester with NBS certified weights
Press. Shock Tube (1 1/2" x 1 1/2" x 21')	14 psi to 100 psi sidestep, duration = 10 ms 40 psi to 250 psi end step, duration = 10 ms	±5%	Quartz type press. transducer
Force	120 lb 1200 lb 12 K lb 60 K lb	.1% of reading to 1/10 FS	NBS certified precision load cells
Force	2000 lb 5000 lb 20 K lb 25 K lb	.1% of reading	NBS certified proving rings

Table 5-54 Testing and Calibration Facilities (contd)

Variable	Range	Accuracy	Standard
Force	1/3 lb to 25 lb 25 lb to 200 lb	Better than 0.01%	NBS certified weights using 1/3 lb and 5 lb std
Acceleration (centrifugal)	175 g max	Better than 0.05% or 0.03 g noise level	Centrifuge, measure arm radius, & angular velocity with counter
Acceleration (vibrational) Low Level	2 to 9000 cps 86 g max	±1 1/2 to 4 kc	Electromagnetic shaker, optical micrometer & NBS referenced accel.
Acceleration (vibrational) Fixed Frequency High Level	3.2 kc, 3.7 kc, 4.6 kc 5.8 kc, 7.4 kc, 9.0 kc 11.1 kc, 13.9 kc, 17.4 kc, 21.0 kc 10,000g to 50,000 g pk	±5%	Capacitance-type NBS type disp. sensor
Acceleration (vibrational) Low Frequency Low Level	0.1 cps to 10 cps 0.01 to 10 g pk	±1%	Period measured with electronic counter. Disp. by metrology methods
Shock	200 g max	10%	Pneumatic actuator. Half-sine wave, sawtooth, or square-wave accel. pulse measured with ref. accel.
Shock	125 g max	10%	Ballistic hammer & ref. accel.

Table 5-54 Testing and Calibration Facilities (contd)

Variable	Range	Accuracy	Standard
Flow	0.03 lb/sec to 50 lb/sec	±1/2% of range	Stop watch, accumultative counter, calib. scale (.02%), freq. counter to monitor flow rate constancy
Flow	50 lb/sec to 200 lb/sec	±1/2% of range	Std flowmeter, freq. counter
Temperature	-190 to +500 °C	±0.08 °C	Plat. resistance thermmeter & Mueller bridge
Temperature	0 to 1450 °C	±0.5° to 2 °C	Plat. vs Plat. - Rhodium thermocouples & dc pot.
Temperature	800 - 2300 °C	±3° to ±7 °C	Ribbon - filament lamps & optical pyrometers
Temperature	Fixed points 0.01°C (H_2O tr.pt) 231.9 °C (Sn) 419.5 °C (Zn) 660. °C (Al) 1083 °C (Cu)	 ±0.0001 °C ±0.01 °C ±0.02 °C ±0.2 °C ±0.3 °C	NBS freezing - point std

5-16 6593D TEST GROUP (DEVELOPMENT)
Air Force Systems Command
United States Air Force
Ewards Air Force Base, California

Table 5-55 Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Acceleration	5 to 5000 cps 0 to 100 g's max 5000 lb force max	1.5 to 5%	Optical Disp. Measuring & Frequency Standard
Flow	0.12 to 350 gal/min (water)	Repeatability	NBS Transfer Flowmeter
Nuclear Radiation			
a. Alpha-Neutron Detection	0-15,000 counts/mim	±10%	Cal. Isotope
b. Gamma Detector	0.2 to 2500 mr/hr	±5%	Cal. Isotope
Pressure	+5 to 10,000 psi vacuum, 0.1 mm hg	±0.1% ± .5%	Oil Dead Weight Tester Hg manometer
Temperature	-259 to +260°C +260 to +1200°C	±0.3°C ±0.5%	Plat. Resist. bulb Std Thermocouple

5-17 INLAND TESTING LABORATORIES
Division of Cook Technological Center
Morton Grove, Illinois

Table 5-56 Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Temperature	-100 to 1000°F	±.5°F	Standard Thermometer
Pressure	0 to 790 mm/hg	±0.2 mm/hg	Haas A-1 Barometer
	5 to 1000 lbs.	±0.1%	Dead Weight Tester
Acceleration	0 to 1000 g's 2 to 5000 cps	±3%	NBS Certified Standard Microphone
Frequency	DC to 100 MC	2 parts in 10^9/day	WWV with Standard Crystal
DC Voltage & Current	0 to 30,000 V 0 to 300 amps	±.015%	NBS Certified K-3 Pot. Standard Cells v Multiplier & Current Multiplier
AC Voltage & Current	0 to 1500 volts 0 to 1000 amps	±0.1% to 1000 cps	Transfer Standards
Resistance	1 to 100,000 ohms	±0.01%	Standard Resistors & Bridges
Capacitance	100 mmf to 1 mfd	±0.2%	Standard Capacitors & Bridges
Sound Press.	2 to 20,000 cps	±1 DB	NBS Certified Std Microphone

Table 5-57 Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Pressure	0 - 30 psi	.05%	Manometer
	100 - 10,000 psi	.01%	Dead Weight Tester
	10,000 - 100,000 psi	.15%	Std Press. Cells
Force	0 - 130,000 lbs	.01%	Dead Weights
	130,000 - 250,000 lbs	.025%	Extended Range Dead Weight Tester
	0 - 800,000 Comp.	.05%	Std Load Cells
	-300,000 Tens.	.05%	
Torque	0 - 50,000 in-lbs	.05%	Dead Weight & Torque Arm
	0 - 400,000 in-lbs	.05%	Std. Load Cells & Torque Arm
Strain	0 - 1,000 u in/in	.5%	Std Bending Beam & Dead Weight
	0 - 2,500 u in/in	.2%	Optical Strain Gage
	0 - 5,000 u in/in	1.0%	Bonded Filament Strain Gage
	0 - 100,000 u in/in	2.0%	Bonded Filament Strain Gage
Transducer Output Voltage	0 - 3 dc mv/v	.025%	Self Bal. Pot. with extended range.
	0 - 4 ac dc mv/v	.05%	
	0 - 30 dc mv/v	.02%	Precision Pot.
Voltage DC	0 - 1.6 volts	.02%	Precision Pot.
Resistance	0 - 99,999,000	.05%	Wheatstone Bridge
Angular Deflection	0 - 60° CW & CCW = 120°	.3%	Geared Calib. Rig

5-19 CRYOGENICS, INC.
Alexandria, Virginia

Table 5-58 Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Temperature	12 °K to 300 °K	.01 °K	NBS Certified Thermometers
	2.2 °K to 5.2 °K	.02 °K	Helium Vapor Press Scale
Pressure	1 Micron Vacuum		McLeod Gage
Resistance	10^{-3} to 10^{-2} ohms	.05%	Std. Resistor & Bridge
Voltage, D.C.	10^{-6} to 10^{-1} volts	.1%	Std. Cells & Precision Pot.
Pressure	1 to 500 lbs	.2%	Dead Wt. Tester
Liquid Level (Cryogenic)	To 36 inches	.060	Visual window in Dewar assembly

The facilities for performing the above noted test programs are located at the company's two locations; Alexandria and Stafford, Va. The Stafford facility is utilized for testing that involves the handling of hazardous media such as liquid hydrogen or where any requirement of the program necessitates remote testing.

The company has an in-house capability for producing liquid helium and hydrogen for the test programs due to the fact that it possesses a Collins Helium-Hydrogen liquefier. Production capability is 8 liters per hour of either liquid helium or hydrogen.

5-20 ENDEVCO CORPORATION
Calibration Service
Pasadena, California

Table 5-59 Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Acceleration (vibration)	5 - 10,000 cps	Error in applied acceleration--- 5 - 900 cps<1.5% 900 - 2000 cps<2.5% 2000 - 5000 cps<3.0% 5000 - 10,000 cps<5.0%	NBS traceability is shown
Acceleration (vibration)	-65°F to +500°F at approx. 100 cps		
Acceleration (vibration)	1 to 100 g at approx. 100 cps		
Cross Axis Sensitivity	at approx. 10 cps		
Acceleration (shock)	100 g to 15,000 g half sine	less than 5%	Impact Drop Tester (see Endevco TD 11/12/60)

Table 5-60 Testing and Calibration Facilities

Variable	Range	Accuracy	*Standard
DC Voltage	0 - 4 volts 4 - 1000 volts	±.0015% or 10 uv ±.003%	NBS Certified 2, 5 NBS Certified 2, 5, 6
AC Voltage	0 - 1000 volts	±.2%, to 4 kc	15
DC Current	0 - 15 amps 0 - 40 ma	±.02% ±.003% or ±.01 ua	1, 3, 8 2, 5
AC Current	10 ma - 5 amps 5 - 20 amps	±.2% ±.25%	15 16
Frequency	10 cps - 10 Mc 10 Mc - 12 Gc	1 count ±3 parts per 10^7 per week ±3 parts per 10^7	WWV Signal, 11, 26 WWV Signal, 11, 26
Resistance	1, 10, 100, 1K, 10K 10 ohms - 1.1 Meg	±.01% ±.05%	NBS Certified 7 31
Inductance	100 uh 1, 10, 100 mh 1 h	±.1% ±.03% ±.05%	NBS Certified 9 " "
Capacitance	100 uufd .001 ufd .01 ufd .1 ufd	±.01% +.1 uufd ±.1% ±.1% ±.1%	NBS Certified 10 " " "
Power (ac & dc)	0 - 4 Kw 0 - 200 w	±.25% to 1.2 Kc ±2.0% to 3 KMc	17, 18 25
Length	0 - 24 inches	Class A gage block tol.	Webber Certified, 12
Mass	1.0 mg - 1 Kg 2 Kg - 10 Kg 1 lb - 50 lb	Class S tol. Class Q tol. Class T tol.	NBS Certified 13, 59, 60 59 59

Table 5-60 Testing and Calibration Facilities (contd)

Variable	Range	Accuracy	*Standard
Temperature	32° - 530°F	±4°F	(a) 34
	530° - 1600°F	±.75% of reading	L. & N. Cert. (a) 34
	-75° - 200°F	±1.5°F	(b) 34
	200° - 700°F	±.75% of reading	(b) 34
	(a) = Chromel & Alumel Thermocouple		
	(b) = Copper & Constantan Thermocouple		
Torque	0 - 100 lb-in	±1.0%	37, 42
	0 - 25 oz-in	±.5%	42
Force	0 - 50 lb (compress)	±1%	37
	0 - 250 lb (tension)	±1%	37, 41, 61
	0 - 1000 lb (tension)	±1%	37, 41, 61
Comparator Magnification	10 x	visual acuity limiting tol. ±.005%	43 ref. to 12
	20 x	±.0025%	43 ref. to 12

Table 5-60 (contd)

*STANDARDS

Reference Standards

1 - Rubicon 2775 Standard Cells (Unsaturated)
2 - Julie Research Labs. SCO-106 Primary Voltage Standard
3 - Rubicon Type B Potentiometer
4 - Rubicon 2795 Volt Box
5 - Julie Research Labs. PVC-504 Precision Voltage Current Potentiometer
6 - Julie Research Labs. VDR-106 Primary Standard Voltage Divider
7 - Gray E-1243-1247 Standard Resistors
8 - Rubicon 1163 Standard Shunt
9 - G. R. 1482 B, H, L, P Standard Inductors
10 - G. R. 1401-A, 509-F, T, L Standard Capacitors
11 - Berkeley 905 WWV Receivers
12 - Webber #24HD Gage Blocks, Class A
13 - Voland and Troemner Weights, Class S
14 - L & N #8784 High Temperature Certified Thermocouple

Transfer Standards

15 - SRI-Model THACH Volt-Ammeter
16 - Weston Model 370 Ammeter
17 - Weston Model 310 Wattmeters
18 - Weston Model 341 Voltmeter

Working Standards

19 - RFL-829 Meter Calibrator
20 - Weston 931 DC Milliammeter
21 - Simpson Model 9 Milliammeter
22 - Simpson Model 9 Ammeter
23 - Weston Model 1 Ammeter
24 - Weston Model 901 Voltimeter
25 - Jones 641-N Calorimetric Wattmeter
26 - Berkeley 7370 & 7580 Frequency Counter equipment
27 - RFL-829 Wheatstone Bridge
28 - John Fluke 301C Precision DC Power Supply
29 - Electro-Measurements 291 Z bridge
30 - G. R. 1454-A Voltage Divider
31 - G. R. 1432-J, K, Q, L Decade Resistors
32 - Empire Devices AT-106D Attenuator
33 - Weinschel AS-1 Precision Attenuator Set

Table 5-60 (contd)

34 - Rubicon 2745 millivolt potentiometer
35 - L & N Thermocouples, Chromel-Alumel and Copper Constantan
36 - Dillon Model L Universal Tester, tension and compression
37 - Dillon X force gages
38 - McCleod Vacuum Gage CVC #GM-100A
39 - Thermometers
40 - Huer Timer
41 - Troemner test weights, class Q & T
42 - Snap-On Tool Co. beam scale torque balance
43 - Optical Comparator magnification check gage
44 - 600A Acme Scientific Monochromatic light source
45 - Optical flats
46 - Master plugs, Midemaster M-2
47 - Screw thread setting plug gages
48 - Thread measuring wires
49 - Micrometers
50 - Surface plates
51 - Angle plate
52 - Sine plate, Robbins B-3-SP
53 - Precision straight edge
54 - Standard gage comparator height gage with test indicator
55 - B & S Crimp height comparator gage
56 - Dermitron standard thickness gages
57 - Rockwell hardness test blocks

Accessory Calibration Equipment

58 - Rubicon 3404-H Galvanometer
59 - Troemner 1751 High capacity balance, 30 kg
60 - Ainsworth Type "T" Analytical banance, 200 g
61 - Radiation Tensile force gage tester, 1000 pounds
62 - Radiation Compression force gage tester, 100 pounds
63 - Radiation Constant temperature standard cell test chamber
64 - Hotpack high temperature furnace

Table 5-61 Testing and Calibration Facilities

Variable	Range	Accuracy	Standard
Temperature	-125°F to +1000°F	0.5°F	Thermocouple Pot.
Pressure	2×10^{-3} to 10^4	1%: 2×10^{-3} to 10 psi 0.1%: 10 to 10^4 psi	Manometer Dead Weight Tester
Sound press. levels	30 to 150 db	0.5 db	Sound level meter
Vibration (acceleration)	0 to 5 KC at 0 to 100 g	1 part in 10^6 ±1%	Optical Means & Freq. Standard Standard Accel.
Mass	0.1 to 20 kilograms	1 gram	Balance
Voltage, DC	250 uv to 2000 volts	0.25%	Prec. Calib.
Voltage, AC	1.5 mv to 1500 volts	0.25%	Prec. Calib.
Resistance	10 uohms to 5×10^6 megohms	0.02%: 10 uohms to 141 ohms 0.05%: 141 ohms to 100 megohms 0.5%: 100 to 1100 megohms 4%: 1100 to 5×10^6 megohms	Std Resistors & Bridge
Flow	0 to 125 gpm	2%	Flowmeter
Capacitance	0.00002 pf to 1.1 uf	0.25%: 0.00002 pf to 1000 pf 0.1%: to 1.1 uf	Std Capacitors & Bridge
Inductance	1 mh to 1000 H	1%	Std Inductors & Bridge

Table 5-61 Testing and Calibration Facilities (contd)

Variable	Range	Accuracy	Standard
Current, DC	2 ua to 20 A	0.25%	Prec. Calib.
Current, AC	1.5 ma to 20 A	0.25%	Prec. Calib.
Frequency	0 to 100 MC	1 part in 10^6	Calib. Freq. Counter

5-23 NORTH HILLS ELECTRONICS, INC.
Glen Cove, New York

North Hills Electronics, Inc. has established a standards laboratory and is initiating a service for industry for the measurement and calibration of any type of equipment requiring measurements of d-c voltage, current and resistance to better than 0.01%. Primary voltage and resistance standards which have been certified by the National Bureau of Standards consist of banks of saturated standard cells certified to 0.0001% and NBS-type resistors kept in a precisely controlled temperature oil bath, whose temperature is maintained at 28° C within 0.01°. North Hills will certify that its measurements are traceable to the National Bureau of Standards.

SECTION VI

REFERENCES

This section presents a consolidated listing of all references which have been footnoted in the preceding section. They are arranged in the numerical order of their appearance in the handbook. The Bibliography (Section VII) does not contain all these references. In some cases they are referenced only to credit a brief statement and other omissions are due completion of Section VII before final draft of preceding sections.

SECTION VI

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SECTION VII

BIBLIOGRAPHY

This Bibliography primarily consists of references pertaining to measurands, specific types of transducers, testing results and calibration techniques. Related handbooks, manuals and compilations are included to assist the reader in transducer state-of-the-art surveys and investigations.

References are arranged alphabetically according to the surname of the principal author. Whenever an author's name was not available, the reference title has been used. The references are numbered consecutively in Arabic numerals, beginning with number one for the first entry, in parallel with the alphabetical order.

An index is provided at the end of the Bibliography. Arabic numberals beside each term in the index indicate the serial number assigned to the references listed in the Bibliography.

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APPENDIX I

IRIG TELEMETRY STANDARDS*

Prepared by

Telemetry Working Group

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* This appendix consists of Parts 1.0 through 5.0 of IRIG Document No. 106-60, approved in November, 1960 and issued in December 1960. A revision of this document dated January 1, 1962 is available, but was received too late for inclusion in this revision of the handbook.

FOREWORD

A standard in the field of telemetry for guided missiles was established in 1948 by the Committee on Guided Missiles of the Research and Development Board (RDB), Department of Defense, and was thereafter revised and extended as necessary as a result of periodic reviews of the standard by the Committee's Working Group on Telemetering of the Panel on Test Range Instrumentation. The last official RDB revision of the standards was published as RDB report MTRI 204/6 dated 8 November 1951. Since the termination of the Research and Development Board, new standards have been prepared by the Inter-Range Instrumentation Group (IRIG). The Steering Committee representing IRIG and the Department of Defense test ranges, has assigned the task of promulgating new or revised telemetry standards to the Telemetry Working Group (TWG). IRIG Document No. 106-60 comprises the current Combined Standards and supersedes the following IRIG Standards:

IRIG Recommendation No. 101-55	Testing for Speed Errors in Instrumentation Type Magnetic Tape Recorders
IRIG Recommendation No. 101-57	Magnetic Recorder/Reproducer Standards
IRIG Recommendation No. 101-60	Magnetic Recorder/Reproducer Standards
IRIG Recommendation No. 102-55	Telemetry Standards for Guided Missiles
IRIG Recommendation No. 102-59	Standards for Pulse Code Modulation (PCM) Telemetry
IRIG Recommendation No. 103-56	Revised Telemetry Standards for Guided Missiles

The Standards have been generated to further compatibility of airborne transmitting equipments and ground receiving and data handling equipments at the test ranges. To this end, it is the recommendation of the Inter-Range Instrumentation Group Steering Committee that Telemetry equipment at the test ranges conform to these standards.

TABLE OF CONTENTS

PART I

RADIO FREQUENCIES
(FREQUENCY PARAMETERS AND CRITERIA FOR DESIGN OF TELEMETRY TRANSMITTER AND RECEIVER SYSTEMS)

1.1 FREQUENCY UTILIZATION

The enclosed parameters and criteria have been devised by the Frequency Coordination Working Group of the Inter-Range Instrumentation Group, with the assistance of members of the Telemetry Working Group, development groups of the three military services, and aircraft industries. The purpose of these parameters is to provide development and coordination agencies with design specifications on which to base equipment development and modification in an effort to insure interference-free operation for all concerned and efficient utilization of the telemetry radio frequency spectrum.

It has long been recognized that the frequency spectrum is a limited entity, a resource which must be conserved. It has been further recognized that frequency utilization is a system problem; the transmitter-receiver link must be considered as a system. Efficiency of spectrum utilization should be a goal; susceptibility to interference should be minimized.

Wasteful use of the spectrum by any system using electromagnetic radiation and reception can have far-reaching effects in many phases of military and civil activities. It is firmly believed that unless the basic philosophy of spectrum conservation is recognized and applied by all agencies in the electronic field, (designers, manufacturers, testers, and users) serious consequences are inevitable.

It is emphasized that these parameters and criteria have been devised for application at military test ranges where congestion of portions of the usable frequency spectrum is a severe problem. It is hoped that, where applicable, these same principles will be applied to other fields outside the scope of instrumentation systems.

1.2 FREQUENCY BAND 216-260 MCS

216-225 mcs - Channel spacing is based on 0.5 mcs separation on the integral and one-half megacycle channels. Assignments

are made on a non-interference basis to established services.

225-260 mcs - A total of 44 (500 kcs) channels, are allocated on a protected basis until 1 January 1970.

A. Efficiency of Spectrum Usage (216-260 mcs Band):

1. TRANSMITTER SYSTEMS (FM/FM; PDM/FM; PAM/FM; and PCM/FM)

a. Maximum rf deviation: plus or minus 125 kcs.

b. Transmitter Frequency Tolerance: The transmitted rf carrier, including drift and all other variables, will be within 0.01% of the assigned carrier frequency.

c. Bandwidth: The bandwidth of the modulated carrier shall not exceed 500 kcs. Carrier components appearing outside the 500 kcs bandwidth must meet the limits for spurious and harmonic emissions as stated in paragraph e. (1) below.

d. Power: 100 watts maximum, never more than absolutely necessary.

e. Spurious and Harmonic Emissions:

(1) Spurious and harmonic emissions from the transmitting antenna system are of primary importance insofar as these criteria are concerned. Spurious and harmonic outputs, antenna conducted (i.e., measured in antenna transmission line) as well as antenna radiated (i.e., measured in free space), shall be limited to the values derived from the formula:

db (down from carrier) = $55 + 10 \log_{10} P_t$, where Pt is the measured power output in watts.

Measurements to determine relative levels of rf power shall be made under the following condition:

(a) Transmitter to be operated into a matched shielded dummy load with a suitable coupling device inserted in the antenna cable to sample the transmitter rf output. As an alternative, the actual antenna can be substituted for the dummy load with provisions being made to remove the field strength meter from the influence of signals radiated from the antenna.

(b) Transmitter to be tested under conditions of zero and full normal modulation.

(c) Commercial, Category Class "I" Field Strength Measuring Equipment, as listed in current MIL-I-6181 will be used.

(2) Spurious, harmonic, and fundamental signals conducted by power leads or radiated directly from equipment units or cable (except antenna) shall be within the limits specified in the current MIL-I-6181.

f. Flexibility of operation: Shall be capable of operating on any of the following frequencies without design modification:

216.5 mcs	223.0 mcs	228.2 mcs	237.8 mcs	248.6 mcs
216.0 mcs	223.5 mcs	229.9 mcs	240.2 mcs	249.1 mcs
217.5 mcs	224.0 mcs	230.4 mcs	241.5 mcs	249.9 mcs
218.0 mcs	224.5 mcs	230.9 mcs	242.0 mcs	250.7 mcs
218.5 mcs		231.4 mcs	243.8 mcs	251.5 mcs
219.0 mcs		231.9 mcs	244.3 mcs	252.4 mcs

219.5 mcs		232.4 mcs	244.8 mcs	253.1 mcs
220.0 mcs	225.0 mcs	232.9 mcs	245.3 mcs	253.8 mcs
220.5 mcs	225.7 mcs	234.0 mcs	245.8 mcs	255.1 mcs
221.0 mcs	226.2 mcs	235.0 mcs	246.3 mcs	256.2 mcs
221.5 mcs	226.7 mcs	235.5 mcs	246.8 mcs	257.3 mcs
222.0 mcs	227.2 mcs	236.2 mcs	247.3 mcs	258.5 mcs
222.5 mcs	227.7 mcs	237.0 mcs	247.8 mcs	259.7 mcs

NOTE: All telemetry assignments within the 225-260 mcs band shall conform with the above assignments. No change in assignments in the 216-225 mcs band is contemplated. However, it should be kept in mind that telemetry assignments in the 216-225 mcs band are on a non-interference basis to other established users.

2. RECEIVER SYSTEMS (FM/FM; PDM/FM; PAM/FM; and PCM/FM):

a. Maximum bandwidth between 60 db points: 600 kcs.

b. Receiver Stability: 0.005%

c. Spurious receiver responses: More than 60 db below fundamental frequency response.

d. Spurious emissions: Oscillator energy, either radiated from the unit or antenna conducted, shall be within the limits specified in current MIL-I-6181.

e. Flexibility of Operation: Shall operate on any of the frequencies listed under Para. I. A. I. f. without design modification.

1.3 FREQUENCY BAND 1435-1535 MCS

Channel spacing of the 1435-1535 mcs band should be on increments of 1 mcs.

The 1435-1535 mcs portion of the band should be reserved primarily for use in connection with aeronautical flight testing of manned aircraft.

The 1486-1535 mcs portion of the band should be reserved primarily for use in connection with aeronautical flight testing of missile and space vehicles.

A. Efficiency of Spectrum Usage

1. TRANSMITTER SYSTEMS (1435-1535 mcs Band)

a. Transmitter frequency tolerance: The transmitter rf carrier, including drift and all other variables, shall be within 0.005% of the assigned carrier frequency.

b. Power: As dictated by intended use, never more than absolutely necessary.

c. Spurious and Harmonic Emissions: Spurious and harmonic emissions from the transmitting antenna system are of primary importance insofar as these criteria are concerned. Spurious and harmonic outputs, antenna conducted (i.e., measured in antenna transmission line) as well as antenna radiated (i.e., measured in free space), shall be limited to the values derived from the formula:

db (down from carrier) = $55 + 10 \log_{10} Pt$, where Pt is the measured power output in watts

d. Spurious, harmonic, and fundamental signals conducted by power leads or radiated directly from equipment units or cables (except antenna) shall be within the limits specified in the current MIL-I-6181 specifications.

e. Measurements to determine relative levels of spurious and harmonic signals shall be made under the following conditions:

(1) Transmitter to be operated into a matched shielded dummy load with a suitable

coupling device inserted in the antenna cable to sample the transmitter rf output. As an alternative, the actual antenna can be subsitituted for the dummy load with provisions being made to remove the field strength meter from the influence of signals radiated from the antenna.

(2) Transmitter to be tested under conditions of zero and full normal modulation.

(3) Commercial, Category Class "I" Field Strength Measuring Equipment, as listed in current MIL-I-6181, will be used.

f. Flexibility of Operation: The rf transmitter shall be capable of operating throughout the entire frequency band 1435-1535 mcs without design modification.

2. RECEIVER SYSTEMS (1435-1535 mcs band)

a. Receiver Stability: 0.001%

b. Spurious receiver responses: More than 60 db below fundamental frequencies.

c. Spurious emissions: Oscillator energy either radiated from the unit or antenna conducted shall be within the limits specified in the current MIL-I-6181.

d. Flexibility of operation: Tunable over the entire 1435-1535 mcs band without design modification and with variable bandwidth selection.

3. BANDWIDTHS

a. In specifying bandwidths, the transmitter and receiver shall be considered as a system. Designer should be required to adhere to rigid

engineering design practices to conserve frequency spectrum. Each system should be subjected to a critical review as to the amount of information contained in a given bandwidth versus type of modulation. Designer should be required to demonstrate and prove system design in order to justify frequency spectrum usage.

b. As a general guideline, it is anticipated that for a deviation of plus or minus 125 kcs a maximum of 1 mcs bandwidth as reference to the 60 db points will be permitted. For a wide band system with a deviation of plus or minus 1.4 mcs, a maximum of 10 mcs as reference to the 60 db points will be permitted. Also, for PCM systems signal bandwidth in cps at 3 db points can be roughly calculated by 1.5 times the bit rate and the bandwidth in cps at the 60 db points can be calculated by 3.6 times the bit rate. It is anticipated the maximum bit rate will be 1×10^6 per second and the minimum bit rate will be 50×10^3 per second. Bandwidth for telemetry systems in excess of 10 mcs as referenced to the 60 db points shall not be used. Bandwidth requirements for transmission of video (television) shall be considered on a case-to-case basis. For further information, refer to IRIG Telemetry Standards.

1.4 FREQUENCY BAND 2200-2300 MCS

Channel spacing of the 2200-2300 mcs band shall be on increments of 1 mcs.

A. Efficiency of Spectrum Usage

1. TRANSMITTER SYSTEMS (2200-2300 mcs)

a. Transmitter Frequency Tolerance: The transmitted rf carrier, including drift and all other

variables, shall be within 0.005% of the assigned carrier frequency.

b. Power: As dictated by intended use, never more than absolutely necessary.

c. Spurious and Harmonic Emissions: Spurious and harmonic emissions from the transmitting antenna system are of primary importance insofar as these criteria are concerned. Spurious and harmonic outputs, antenna conducted (i.e., measured in antenna transmission line) as well as antenna radiated (i.e., measured in free space), shall be limited to the values derived from the formula:

db (down from carrier) = $55 + 10 \log_{10} Pt$, where Pt is the measured power output in watts

d. Spurious, harmonic, and fundamental signals conducted by power leads or radiated directly from equipment units or cable (except antenna) shall be within the limits specified in the current MIL-I-6181 specifications.

e. Measurements to determine relative levels of spurious and harmonic signals shall be made under the following conditions:

(1) Transmitter to be operated into a matched shielded dummy load with a suitable coupling device inserted in the antenna cable to sample the transmitter rf output. As an alternative, the actual antenna can be substituted for the dummy load with provisions being made to remove the field strength meter from the influence of signals radiated from the antenna.

(2) Transmitter to be tested under conditions of zero and full normal modulation.

(3) Commercial, Category Class "I" Field Strength Measuring Equipment, as listed in current MIL-I-6181, will be used.

f. Flexibility of Operation: The rf transmitter shall be capable of operating throughout the entire frequency band 2200-2300 mcs without design modification.

2. RECEIVER SYSTEMS (2200-2300 mcs)

a. Receiver Stability: 0.001%

b. Spurious receiver response: More than 60 db below fundmental frequencies.

c. Spurious emissions: Oscillator energy either radiated from the unit or antenna conducted shall be within the limits specified in the current MIL-I-6181.

d. Flexibility of Operation: Tunable over the entire 2200-2300 mcs band without design modification and with variable bandwidth selection.

3. BANDWIDTHS

a. In specifying bandwidths, the transmitter and receiver shall be considered as a system. Designer should be required to adhere to rigid engineering design practices to conserve frequency spectrum. Each system should be subjected to a critical review as to the amount of information contained in a given bandwidth versus type of modulation. Designer should be required to demonstrate and prove system design in order to justify frequency spectrum usage.

b. As a general guideline, it is anticipated that for a deviation of plus or minus 125 kcs, a maximum for 1 mcs bandwidth as reference to the 60 db points will be permitted. For a wide band system with a deviation of ± 1.4 mcs a maximum of 10 mcs as referenced to the 60 db points will be permitted. Also, for PCM systems, signal bandwidth in cps at 3 db points can be roughly calculated by 1.5 times the bit rate and the bandwidth in cps at the 60 db points can be calculated by 3.6 times the bit rate. It is anticipated the maximum bit rate will be 1×10^6 per second and the minimum bit rate will be 50×10^3 per second. Bandwidth in excess of 10 mcs for telemetry systems as reference to the 60 db points shall not be used. Bandwidth requirements for transmission of video (television) shall be considered on a case-to-case basis. For further information refer to the IRIG Telemetry Standards.

PART II

FM/FM or FM/PM STANDARDS

2.1 GENERAL

These telemetry systems are of the frequency division multiplex type. That is, a radio frequency carrier is modulated by a group of subcarriers, each of a different frequency. The subcarriers are frequency modulated in a manner determined by the intelligence to be transmitted. One or more of the subcarriers may be modulated by a time division multiplex scheme (commutation) in order to increase considerable the number of individual data channels available in the system. The modulation of the radio frequency carrier may be by either of two methods: frequency modulation or phase modulation.

2.2 SUB-CARRIER BANDS

Eighteen standard sub-carrier band center frequencies with accompanying information on frequency deviation and nominal intelligence frequency response are specified in Table I-1. It is intended that the standard FM/FM receiving stations at the test ranges be capable of simultaneously demodulating a minimum of any twelve of these sub-carrier signals.

The nominal frequency response listed for each band is computed on a basis of maximum deviation and a deviation ratio of five, and it is intended that the standard receiving station be capable of demodulating data with these frequency responses. However, it should be remembered that the actual frequency response obtainable is dependent on many things, such as the actual deviation used, the characteristics of filters, etc. The primary reason for specifying a frequency response is to insure that elements in the receiving station such as filters and recording oscillographs provide the frequency responses shown in Table I-1.

2.2.1 While deviation ratios of five are recommended, deviation ratios as low as one or less may be used, but low signal-to-noise ratios, possible increased harmonic distortion and cross-talk must be expected.

2.2.2 The eighteen bands were chosen to make the best use of present equipment and the frequency spectrum. There is a ratio of approximately 1.3 : 1 between center frequencies of adjacent bands except between 14.5 kilocycles and 22 kilocycles, where a larger gap was left to provide for compensation tone for magnetic tape recording. The deviation has been kept at ±7.5% for all bands with the option of ±15% deviation on the five higher bands to provide for transmission of higher frequency data. When this option is exercised on any of these five bands, certain adjacent bands cannot be used, as listed in the footnote to Table I-1.

2.2.3 It is likely that certain applications will make amplitude pre-emphasis of some subcarrier signals desirable, and it is recommended that the ground equipment be capable of accommodating this pre-emphasized signal. A de-emphasis capability of up to 9 db per octave may be required.

2.3 AUTOMATIC CORRECTION OF SUBCARRIER ZERO AND SENSITIVITY DRIFT

2.3.1 General

In some cases, it is found necessary to automatically correct for subcarrier zero and sensitivity drift during the course of a test. To provide for such corrections calibration signals are applied to the subcarrier oscillators which must have such correction by an in-flight calibrator. In addition, a signal is required to arm and actuate the automatic correction equipment in the receiving or data playback station. Automatic correction command and calibration signals, when employed, shall conform to the following standards:

2.3.2 Automatic Correction Command

A standard IRIG subcarrier band multiplexed with the data subcarriers shall be employed to transmit the correction commands. Modulation of the command subcarrier shall be as follows:

2.3.2.1 Command Sequence

The command sequence shall be: "data," "correct for zero drift," "correct for sensitivity drift," "data."

Table I-1 Sub-Carrier Bands

Band	Center Freq. (cps)	Lower Limit (cps)	Upper Limit (cps)	Max. Deviation (percent)	Freq.* Response (cps)
1	400	370	430	±7.5	6.0
2	560	518	602	"	8.4
3	730	675	785	"	11.
4	960	888	1,032	"	14.
5	1,300	1,202	1,399	"	20.
6	1,700	1,572	1,828	"	25.
7	2,300	2,127	2,473	"	35.
8	3,000	2,775	3,225	"	45
9	3,900	3,607	4,193	"	59.
10	5,400	4,995	5,805	"	81.
11	7,350	6,799	7,901	"	110.
12	10,500	9,712	11,288	"	160.
13	14,500	13,412	15,588	"	220
14	22,000	20,350	23,650	"	330
15	30,000	27,750	32,250	"	450
16	40,000	37,000	43,000	"	600
17	52,500	48,562	56,438	"	790
18	70,000	64,750	75,250	"	1,050

(continued)

* Frequency response given is based on maximum deviation and deviation ratio of five (See text for discussion).

Table I-1 Sub-Carrier Bands (continuation)

Band	Center Freq. (cps)	Lower Limit (cps)	Upper Limit (cps)	Max. Deviation (percent)	Freq. * Response (cps)
A.	22,000	18,700	25,300	±15.	660.
B.	30,000	25,500	34,500	"	900.
C.	40,000	34,000	46,000	"	1,200.
D.	52,500	44,625	60,375	"	1,600
E.	70,000	59,500	80,500	"	2,100

**Bands A through E are optional and may be used by omitting adjacent bands as follows:

Band Used	Omit Bands
A	13, 15 and B
B	14, 16, A and C
C	15, 17, B and D
D	16, 18, C and E
E	17 and D

NOTE:

In the process of magnetic tape recording of the above listed subcarriers at a receiving station, provision may also be made to record a tape speed control tone and tape speed error compensation signals as specified in part (6) of these standards.

2.3.2.2 Command Subcarrier Modulation

2.3.2.2.1 The "data command is indicated by the command subcarrier operating at its nominal center frequency ±0.75% of f_c.

2.3.2.2.2. The "correct for zero drift" command is indicated by a displacement of the command subcarrier upward in frequency to f_c plus (6.75% f_c ± 0.75% f_c). This command shall occupy 50% of the total calibration time interval.

2.3.2.2.3 The "correct for sensitivity drift" command is indicated by a displacement of the command subcarrier downward in frequency to f_c minus (6.75% f_c ± 0.75% f_c). This command shall occupy 50% of the total calibration time interval.

2.3.3 Data Subcarrier Calibration

2.3.3.1 Calibration Sequence

The calibration sequence shall be: "data," "center frequency," "80% of full scale," "data."

2.3.3.2 Subcarrier Modulation (Ref. Fig. I-1)

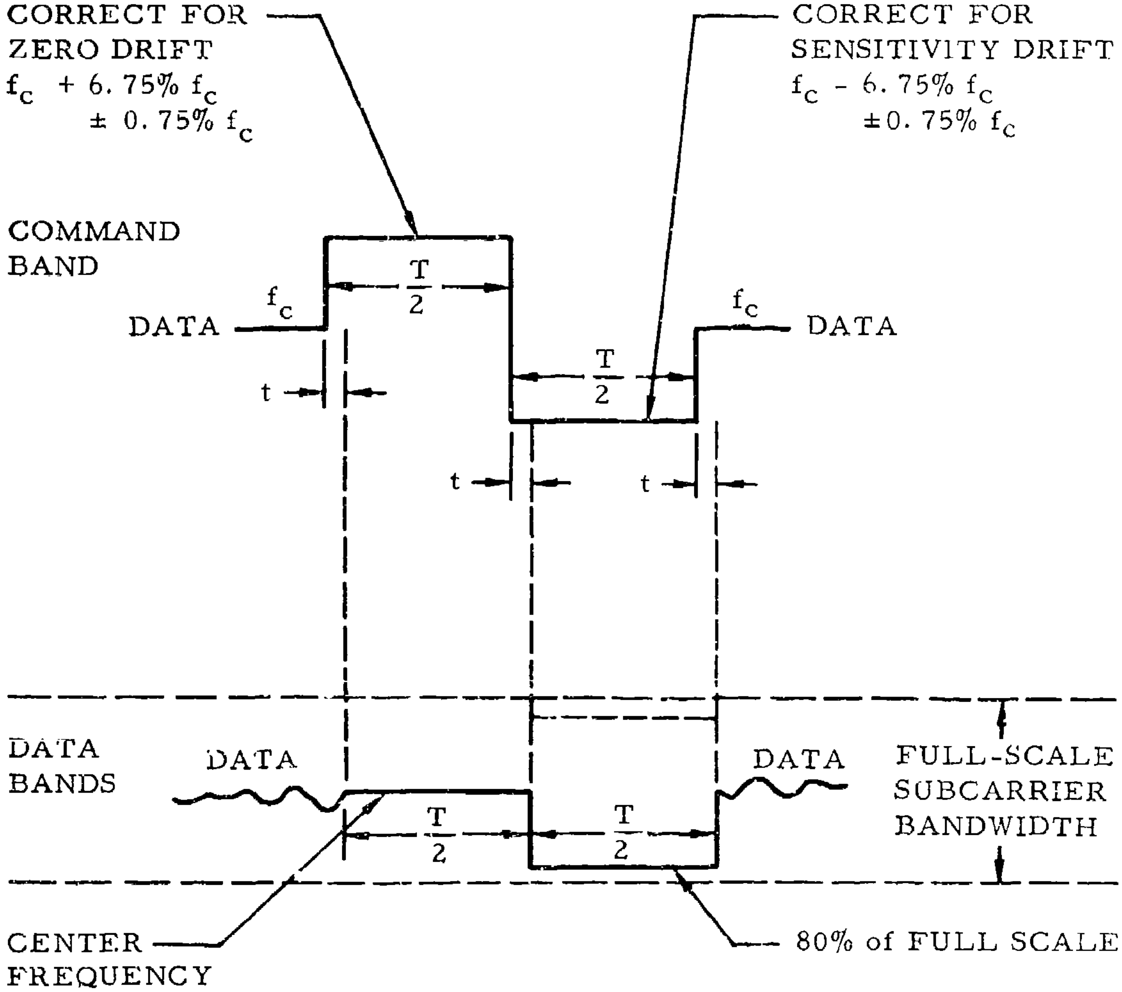
2.3.3.2.1 The "data" position is the subcarrier connected to its normal data source (transducer, commutator, etc.).

2.3.3.2.2 The "center frequency" position is the subcarrier connected to a signal source which would result in the nominal subcarrier center frequency if no zero or sensitivity drift has occurred. The subcarrier shall remain at this position for 50% of the calibration interval.

2.3.3.2.3 The "80% of full scale" position is the subcarrier connected to a signal source which would result in a frequency f_c ± 30% of full scale bandwidth if no zero or sensitivity drift had occurred. The subcarrier shall remain at this position for 50% of the calibration interval.

2.3.3.3 Phasing of Calibration Signal

The data subcarrier calibration signals shall lag the command signals by 200 milliseconds (Ref. Fig. I-1)



t = 200 MILLISECONDS, +50, -0 ms
T = 5 SECONDS FOR ±10% CORRECTIONS PER CALIBRATE CYCLE

Fig. I-1 Automatic Zero and Sensistivity Drift Calibration Command and Data Channel Signals

2.3.4 Correction Capability

Automatic correction equipment shall be capable of correcting zero and sensitivity drift errors of up to ±10% of full scale subcarrier bandwidth per calibrate cycle.

2.3.4.1 Calibration Duration

For maximum (±10%) zero and sensitivity drift correction, the calibrate interval shall be 5 seconds. Where maximum corrections per calibrate cycle are not required, the calibration interval may be correspondingly reduced.

2.4 PAM/FM/FM COMMUTATION

Commutation (time division multiplexing) may be used in one or more subcarrier bands. A nearly limitless variety of commutation schemes could be devised, but a few relatively simple methods will satisfy most telemetry needs. The specifications listed below for commutation were chosen to give a maximum flexibility consistent with presently available equipment and techniques, and it is intended that, in order to limit the varieties which must be handled at test ranges, the following restrictions on commutation be observed:

2.4.1 Commutation rates as listed in Table I-2 shall not be exceeded on each subcarrier.

2.4.2 Recommended Sample Rates

Recommended commutation rates listed in Table I-2 require the use of discriminator output low pass filters with cut off frequencies equal to four times the specified commutation rate.

2.4.3 Separated Data

Where required, automatic channel separation (decommutation) equipment shall be provided in the receiving station to process commutated signals that conform to the following characteristics: (See Fig. I-2 and Table I-3).

Table I-2. Commutation Rates - Unseparated Data

Band Number	Center Frequency (cps)	Sample Duration (milliseconds) Recommended Values	Commutation Rate (samples per second) Recommended Values
1	400	170	6.0
2	560	120	8.4
3	730	91	11
4	960	70	14
5	1,300	51	20
6	1,700	39	25
7	2,300	29	35
8	3,000	22	45
9	3,900	17	59
10	5,400	12	81
11	7,350	9.1	110
12	10,500	6.4	160
13	14,500	4.6	220
14	22,000	3.0	330
15	30,000	2.2	450
16	40,000	1.7	600
17	52,500	1.3	790
18	70,000	0.95	1,050

(continued)

Table I-2. Commutation Rates - Unseparated Data (continuation)

Band Number	Center Frequency (cps)	Sample Duration (milliseconds) Recommended Values	Commutation Rate (samples per second) Recommended Values
A	22,000	1.5	660
B	30,000	1.1	900
C	40,000	0.83	1,200
D	52,500	0.63	1,600
E	70,000	0.48	2,100

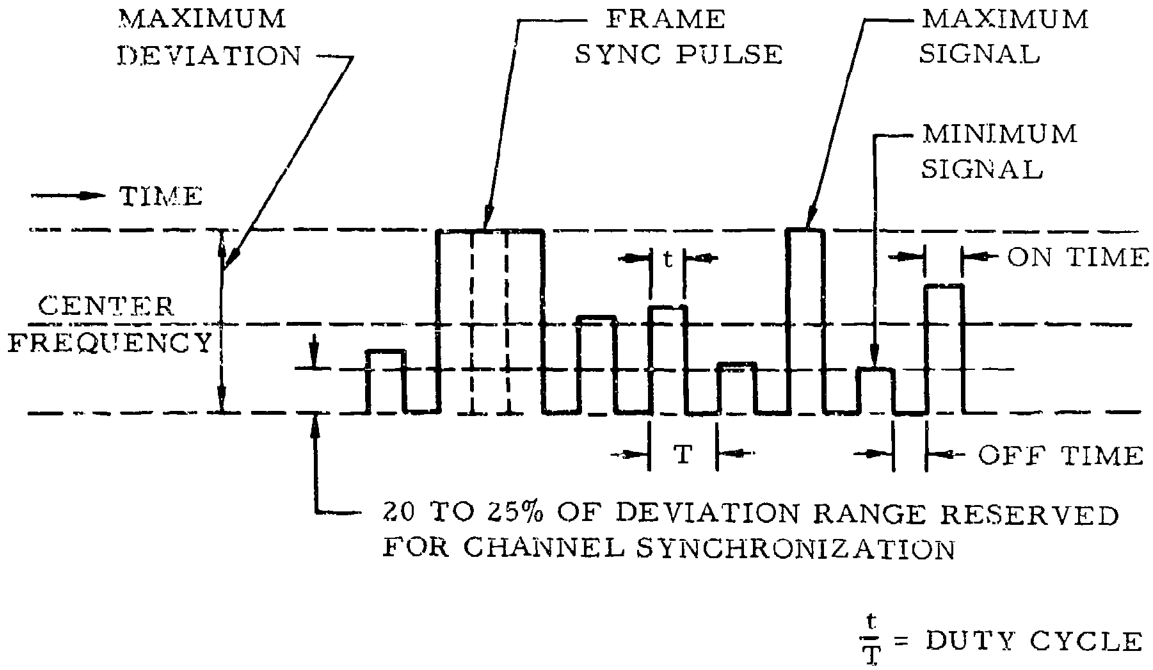


Fig. 1-2 PAM Pulse Train Waveform

2.4.3.1 The total number of samples per frame (number of segments of a mechanical commutator) and the frame rates shall be one of the combination shown in Table I-3. If a higher commutation rate is required for certain information, two or more samples per frame (equally spaced in time) can be used to represent one telemetered function at the expense of the total number of information channels. This process is referred to as cross-strapping or super-commutation.

2.4.3.2 The commutation pattern in the subcarrier frequency versus time domain, shall be as shown in Figure 1-2.

2.4.3.3 A frame synchronizing pulse of full scale amplitude and duration equal to two "on" periods plus one "off" period shall be provided once every frame, as shown in Fig. 1-2.

2.4.3.4 The commutator speed (or frame rate) shall not vary more than plus 5.0% to -15% from the nominal values given in Table I-3.

2.4.3.5 The duty cycle shall be 40% to 65%.

2.4.3.6 A channel synchronization pedestal is required for automatic decommutation (See Fig. 1-2).

2.5 In Flight Zero and Full Scale Calibration

On all PAM commutators, channels one and two, following the synchronizing pulse are recommended for zero and full scale calibration respectively.

Table I-3. Commutation Specification for Automatic Decommutation

No. of Samples per Frame*	Frame Rate Frames (per second)	Commutation Rate** (samples per second)	Lowest Recommended Subcarrier bands (cps)
18	5	90	14, 500
18	10	180	22, 000(± 15%) or 30, 000(± 7. 5%)
18	25	450	30, 000(± 15%) or 70, 000(± 7. 5%)
30	2. 5	75	10, 500
30	5	150	22, 000(± 7. 5%)
30	10	300	22, 000(± 15%) or 40, 000(± 7. 5%)
30	20	600	40, 000(± 15%)
30	30	900	70, 000(± 15%)

*The number of samples per frame available to carry information is two less than the number indicated, because the equivalent of two samples is used in generating the frame synchronizing pulse.

** Frame rate times number of samples per frame.

PART III

PDM/FM or PDM/PM or PDM/FM/FM STANDARD

3.1 General

The pulse duration modulation (PDM) systems are intended for use where a strictly time division multiplex system can meet the bulk of the telemetry requirements of a given application. A relatively large number of information channels can be accommodated, but a relatively low frequency response capability in comparison with the subcarrier channels of the FM/FM system.

3.2 PDM/FM or PDM/PM

The following are the specifications for the pulse duration modulated signal:

Number of samples per frame*	30	45	60	90
Frame Rate (frames/sec.)	30	20	15	10
Commutation rate (samples/sec.)**	900	900	900	900

The amplitude of the measurands being transmitted in each channel shall determine the duration of the corresponding pulses. The relation between measurands and pulse duration should, in general, be linear.

Minimum pulse duration (zero level information):	90 ± 30 microseconds
Maximum pulse duration (maximum level information):	700 ± 50 microseconds
Pulse rise and decay time (measured between 10% and 90% levels):	10 to 20 microseconds (constant to ±1 microseconds for a given transmitting set).

* The number of samples per frame available to carry information is two less than the number indicated because the equivalent of two samples is used in generating the frame synchronizing pulse.

** Commutation rate is equal to the frame rate multiplied by the number of samples per frame.

3.2.1 The time interval between the leading edges of successive pulses within a frame shall be uniform from interval to interval within plus or minus 25 microseconds. This time interval shall have a nominal period equal to one divided by the total sampling rate.

3.2.2 The commutator speed or frame rate shall not vary more than plus 5.0% to -15.0% from nominal.

A frame synchronizing interval equal to two successive pulse time intervals shall exist in the train of pulses transmitted, to be used for synchronization of the commutator and the decommutator. A representation of the pulse train waveform is shown in Fig. 3.

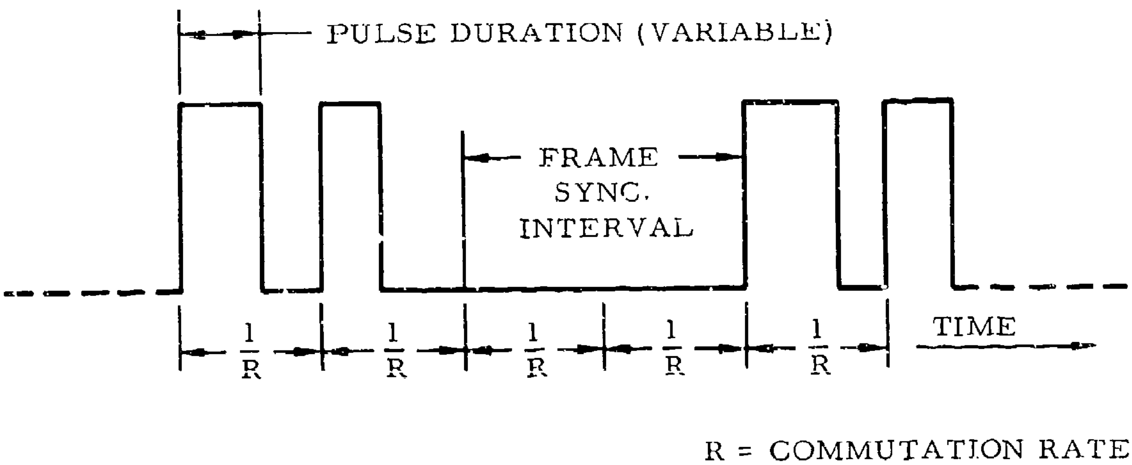


Fig. I-3 PDM Pulse Train Waveform

3.3 PDM/FM/FM

Pulse duration modulation (DPM) systems may also be employed on the 15% deviation channels of the standard FM/FM multiplex

systems. When so used, they are designated as PDM/FM/FM Telemetry. It should be recognized that this application of PDM is wasteful of bandwidth and that it places three wide band modulation systems in cascade. Gaussian type output low pass filters should be used at the discriminator outputs for this application.

3.3.1 The recommended subcarrier channels for this application are bands B, C, D, or E. Operating criteria for use of these specific bands are specified in Table I-4.

Table I-4. PDM Modulation of FM/FM Sub-Carrier Channels

Samples Per Second	Channel Allocation	FM/FM Channel	Deviation Utilized	Recommended Value of Min. Pulse Length
900	B	30.0 kcps	±7.5%	200 +30 microseconds minus none
900	C	40.0 kcps	±7.5%	170 +30 microseconds minus none
900	D	52.5 kcps	±7.5%	150 +30 microseconds minus none
900	E	70.0 kcps	±7.5%	110 +30 microseconds minus none

Satisfactory performance is contingent upon use of optimum output low pass filters.

Reference: "The Transmission of Pulse Width Modulated Signals Over Restricted Bandwidth Systems." <u>IRE Transactions on Telemetry and Remote Control.</u> Volume TRC-3, No. 1, April 1957.

3.3.2 Time interval variation between leading edges of successive pulses. Section 3.2.1 shall apply.

3.3.3 Commutation Speed

Section 3.2.2 shall apply.

3.4 In-Flight Zero and Full Scale Calibration

On all PDM Commutators, channels one and two, following the synchronizing pulse, are recommended for zero and full scale calibration respectively.

PART IV

PAM/FM or PAM/PM STANDARDS

These standards will be forthcoming. Copies may be requested from:

Secretariat
Inter-Range Instrumentation Group
White Sands Missile Range
New Mexico

PART V

PCM STANDARDS

5.1 GENERAL

Pulse code modulation (PCM) data specified in these standards shall be transmitted as serial binary coded, time division multiplexed samples.

5.2 BIT RATE VERSUS RECEIVER INTERMEDIATE FREQUENCY (IF) BANDWIDTH (3 db points)

Selections of bit rates and corresponding receiver IF bandwidth shall be made from those listed in Table I-5 below. Only those discrete receiver IF bandwidths listed shall be used (optional below 12,500 cps). The selections in Table I-5 have been chosen with the consideration that automatic tracking of radio frequency (rf) carrier drift or shift will be utilized in the receiver.

Table I-5 Bit Rate and Receiver IF Bandwidth (3 db points)

System Type	Bit Rate (bits per second)	Receiver IF Bandwidth (cps)
A	8,000 and lower	12,500 (and as required for lower bit rates)
B	8,000 to 65,000	25,000 - 50,000 - 100,000
C	50,000 to 330,000	100,000 - 300,000 - 500,000
D	320,000 to 800,000	500,000 - 1,000,000* - 1,500,000*

* For use in 1435-1535 mcs and 2200-2300 mcs telemetry frequency bands only.

5.2.1 It is recommended that for practical design considerations, a bit rate equal to the receiver IF bandwidth (3 db points) divided by a factor ranging from 1.5 to 3.0 be used. The bandwidth - bit rate relationships in Table I-5 were selected on this basis.

5.2.2 For reference purposes, a receiver IF signal-to-noise ratio (power) of approximately 15 db will result in a bit error probability of about one bit in 10^6. A two db change (increase or decrease) in this signal-to-noise ratio will result in an order of magnitude change (10^7 or 10^5, respectively) in the bit error probability.

5.2.3 It should be recognized that the range of factors 1.5 to 3.0 recommended in paragraph 5.2.1 may result in a compatibility problem when using current frequency modulation (FM) receivers for standard IRIG FM/FM and PDM/FM systems as well as PCM/FM systems designed in accordance with the standard herein. Modifications may be required to video amplifier stages and other circuitry as necessary.

5.3 BIT RATE STABILITY

The change in bit rate shall not exceed 1.0% of the nominal bit rate. It is recommended that rate of change of bit rate not exceed 0.1% of the nominal bit rate per second. (The above values are tentative and subject to change).

5.4 WORD AND FRAME STRUCTURE

The number of bits per frame shall not exceed 2048 including those used for frame synchronization. The frame length selected for a particular mission shall be kept constant. Word length for any given channel can range from 6 to 64 bits but shall be kept constant for any given channel for a particular mission. It is recommended that an odd parity bit be included where a higher order of confidence in bit transmission is desired.

5.5 SYNCHRONIZATION

Frames shall be identified by a unique frame synchronization word. The length of word should be proportional to the length of the frame, since longer frames require longer synchronization patterns in order to provide adequate probability of acquisition. It is recommended,

that a repeated 11-bit Barker code word be utilized with minimum length 11-bit plus (complement 11-bit), and maximum length 11-bit plus (complement 11-bit) plus (complement 11-bit). Patterns less than maximum length may be formed by progressively deleting the latter bits of the second complement 11-bit word. The 11-bit Barker code is 11100010010 and its complement is 00011101101.

5.5.2 To facilitate rapid bit synchronization, it is recommended that, for a Non-Return-to-Zero (NRZ) code, a change in state occur at least once every 64 bits. Such change in state may be provided by odd parity, fixed programming, the guarantee that all data will not simultaneously go to zero or full-scale, etc.

5.6 SUPER-COMMUTATION AND SUBCOMMUTATION

5.6.1 Super-commutation and subcommutation are acceptable methods for exchanging the number of measurands and sampling rate. A selected coded word shall be used to indicate the beginning of the subcommutator sequence. It is recommended that a repeated 7-bit Barker code word be utilized with minimum length 7-bit plus (complement 7-bit) and maximum length 7-bit plus (complement 7-bit) plus (complement 7-bit). Patterns less than maximum length may be formed by progressively deleting the latter bits of the second complement 7-bit word. The 7-bit Barker code is 1110010 and its complement is 0001101.

5.6.2 The number of bits per subcommutation frame shall not exceed 2048 including those used for subcommutation frame synchronization. The number of channels in a subcommutation frame shall not exceed 130 including that used for subcommutation frame synchronization.

5.7 PRE-MODULATION FILTERING

A low pass filter with cutoff frequency (3 db) equal to one-half the nominal bit rate shall be used before the transmitter modulator. The use of a maximally linear phase response type filter with a final slope of 36 db per octave is recommended.

5.8 RF CARRIER MODULATION

5.8.1 The rf carrier modulation method shall be frequency modulation (FM). Since frequency-shift-keying (FSK), where modulation

is accomplished by switching from one discrete frequency to another, is not compatible with pre-modulation filtering, it is not acceptable. Other modulation methods applicable to PCM (NRZ) transmission have not been proven and therefore are not included at this time.

5.8.2 Frequency modulation of the carrier shall be of the type where:

The carrier is deviated to the higher frequency deviation limit to transmit a "one" and to the lower frequency deviation limit to transmit a "zero." Once a frequency deviation limit is reached for either a "one" or a "zero," the resulting frequency remains constant for consecutive like bits.

APPENDIX II

GLOSSARY

OF

TELEMETRY TRANSDUCER TERMS

Prepared by

Telemetry Working Group

IRIG

Acknowledgements

The Transducer Committee of the Telemetry Working Group gratefully acknowledges the assistance of transducer's users and manufacturers who co-operated in preparation of the Transducer Glossary.

The Transducer terms herein contained are subject to revision one year from date of approval.

The Transducer Glossary was generated as an aid towards effective communication of engineers in the field of Telemetry Transducer Instrumentation.

ABSOLUTE SYSTEM OF UNITS

A system of units in which a small number of units are chosen as fundamental and all other units are derived from them.

ACCELERATION

The time rate of change in velocity and/or direction.

ACCELERATION SENSITIVITY

The difference between the output at zero acceleration and the output measured at a given steady state acceleration. Usually expressed in per cent of full-scale output per "g." May be expressed as output difference under acceleration at zero stimulus or at some other value of the stimulus.

ACCELEROMETER

A transducer which measures one or more components of acceleration.

ACCURACY

Freedom from mistakes or errors. A measure of conformity to a specified value.

ACTIVE LEG

An electrical element within a transducer which changes its electrical characteristics as a function of the application of stimulus.

ALTITUDE

The perpendicular distance from a reference line or level to an object or point in space.

ANALOG OUTPUT

Transducer output in which the amplitude is continuously proportional to the stimulus, the proportionality being limited by the resolution of

the transducer. Distinguished from digital output.

ANGULAR VELOCITY

The time rate of change of angular displacement expressed in radians per second and generally designated by the Greek letter omega (ω).

ARMATURE

The member, in certain transducers, which is displaced by the collected forces in the force-summing element and which in turn changes the characteristics of the electrical elements as a function of the applied stimulus. Also the component which completes the magnetic path in "E" core inductive coils.

ATTENUATION

The relationship, in complex notation, between the input stimulus and the output response of a system or device. Attenuation generally implies amplitude and power reduction and corresponding phase change of a stimulus or signal between two points of the system or device.

BEST FIT STRAIGHT LINE

A line chosen to represent the sensitivity of a transducer and from which non-linearity errors may be calculated. The line is chosen such that the response curve contains as much of the function above the line as below the line.

BEST FIT STRAIGHT LINE WITH FORCED ZERO

The line from which zero based linearity is calculated.

BEST FIT STRAIGHT LINE WITH "Y" INTERCEPT

A best fit straight line the position of which is fixed by a given output of the transducer at zero measurand. Non-linearity errors may be expressed as deviation from such a line. The phrase "best fit straight line with 'Y' intercept" is often used to indicate non-linearity error calculated from such a line.

BONDED PICKUP

The preferred term is bonded transducer.

BONDED STRAIN GAGE

Strain-sensitive elements arranged to facilitate bonding to a surface in order to measure applied stresses.

BRIDGE RESISTANCE

The resistance of each element of a transducer whose configuration is that of Wheatstone bridge, also the output resistance of said device.

BURST PRESSURE

The pressure at which the housing or force-summing member of a pressure transducer fails to support the associated stresses, so that a rupture or leak results.

CASE PRESSURE

The total differential pressure between the pressure in the internal cavity of a transducer and the ambient pressure. The term is commonly used to summarize the limiting combined differential and/or line pressure capabilities of differential transducers.

CENTER OF SEISMIC MASS

The point in the seismic mass where acceleration and/or gravitational forces are summed. The center of seismic mass provides the reference from which the radius is determined when calculating, or applying, linear acceleration levels generated by a centrifuge. The center of seismic mass is often determined empirically by spinning the accelerometer in the center of a centrifuge and observing the position of the instrument when its output is equivalent to zero acceleration.

CRITICAL DAMPING

The value of damping which provides the most rapid transient response without overshoot.

CROSS ACCELERATION

The preferred term is transverse acceleration.

CROSS SENSITIVITY

The preferred term is transverse sensitivity.

DAMPED NATURAL FREQUENCY

The frequency at which a system with a single degree of freedom will oscillate, in the presence of damping, upon momentary displacement from the rest position by a transient force. In accelerometers, the damped natural frequency is generally determined by means of the 90° phase shift method. That is, by vibrating the instrument at a constant amplitude and observing the lowest frequency where there is a 90° phase shift between the accelerometer output and the applied vibration which is monitored with a velocity coil or some other suitable reference signal.

DAMPING

Referes to the resistance, friction or similar cause that diminishes the amplitude of an oscillation with each successive cycle.

DAMPING FACTOR

The ratio of any one amplitude and the next succeeding it in the same sense or direction, when energy is not supplied on each cycle. In second-order systems with single degree of freedom the decrement is constant. The amplitude decays as $e^{-\delta t}$

Where: t = time
δ = logarithmic decrement

DAMPING RATIO

The ratio of actual damping to critical damping. May be expressed as the ratio of output under static conditions to twice the output at the lowest frequency where a 90° phase shift is observed.

DEAD VOLUME

The total volume of the pressure port cavity of a transducer at the rest position, i. e., no stimulus applied.

DIGITAL OUTPUT

Transducer output that represents the magnitude of the stimulus in the form of a series of discrete quantities coded to represent digits in a system of notation. Distinguished from analog output.

DIGITIZER

A device which converts analog data into numbers expressed in digits in a system of notation.

DOUBLE AMPLITUDE

In the field if vibratory acceleration the term double amplitude is employed to indicate the total, or peak-to-peak, dimensional displacement of a vibrating structure.

DRIFT

A change in output attributable to any cause.

DYNAMIC RESPONSE

The preferred term is frequency response.

DYNAMIC TEST

A test performed on accelerometers by means of which information is gathered pertaining to the over-all behavior, frequency response and/or natural frequency of the device.

"E" CORE

The configuration of laminations used in certain inductive transducers which resembles the form of the capital Roman letter "E".

ELECTROMAGNETIC DAMPING

See magnetic damping.

END POINTS

The output values obtained at the points where the magnitude of the stimulus equals the limits of the rated range of the transducer.

END POINT LINEARITY

The manner of expressing deviations from a straight line drawn between the end points of a calibration curve.

ERROR

The difference between the indicated value and the true value of the measurand.

ERROR BAND

An error value, usually expressed in per cent of full scale, which defines the maximum allowable error permitted for a specified combination of transducer parameters.

ERROR CURVE

A plot of the difference between the indicated and true values of the measurand versus the true value of the measurand.

EXCITATION ENERGY

The external electrical energy required for the proper operation of a transducer.

"F" FACTOR

The slope of the straight line from which non-linearity is calculated. Given as microvolts output per volt excitation per unit stimulus.

FLAT FREQUENCY RESPONSE

Response of a system to a constant amplitude function which varies in frequency. The response is "flat" if it varies within specified limits of amplitude, usually specified in decibels from a reference quantity.

FLUID DAMPING

Accelerometer damping obtained through the displacement of fluid by the mass and the accompanying dissipation of heat.

FREQUENCY-MODULATED OUTPUT

An output which is obtained in the form of a deviation from a center frequency, where the deviation is proportional to the applied stimulus.

FREQUENCY RESPONSE

The portion of the frequency spectrum which can be sensed by a device within specified limits of amplitude error.

FRICTIONAL ERRORS

The difference in resistance or output between readings obtained prior to and immediately after tapping an instrument while applying a constant stimulus. Particularly applicable to potentiometric transducers.

FULL EXCURSION

The application of measurand, in a controlled manner, over the entire range of a transducer.

FULL-SCALE OUTPUT

The algebraic difference in electrical output between the maximum and minimum values of measurand over which the instrument is calibrated. When the sensitivity slope is given by any other line than the end point sensitivity, full scale expresses the algebraic difference, for the span of the instrument, which is calculated from the slope of the straight line from which non-linearity is determined.

GAGE FACTOR

A measure of the transfer function of strain-sensitive resistive materials. Numerically expressed as:

$$GF = \frac{\Delta r/R}{\Delta l/L}$$

Where $\Delta r/R$ = unit change in resistance
$\Delta l/L$ = unit change in length

The term is often used as synonymous with the gage sensitivity.

GAGE PRESSURE

A differential pressure measurement in which the ambient pressure provides the reference. Also, a pressure in excess of the standard atmospheric pressure at sea level, e.g., 14.7 psia.

HYSTERESIS ERROR

The maximum difference between the readings of the transducer for a fixed value of the measured stimulus taken when the stimulus is increasing and when it is decreasing. Hysteresis error is often expressed in per cent of full scale.

INACCURACY

The term sometimes used to indicate deviations from a specific reference in which "all causes" of error attributable to the instrument are lumped. It is too broad a concept to be applied properly,

due to the multitude or parameters that must be specified as inclusions c · exceptions. Furthermore, corresponding magnitude for each condition would also be required.

INACTIVE LEG

An electrical element within a transducer which does not change its electrical characteristics as a function of the applied stimulus. Specifically applied to elements which are employed to complete a Wheatstone bridge in certain transducers.

INFINITE RESOLUTION

The ability to provide a stepless, continuous output over the entire range of a device.

INSTABILITY

It is preferred that this term not be used. See stability.

INTERNAL PRESSURE

Same as case pressure.

INTERVAL CALIBRATION

The preferred term is step calibration.

LINEARITY

A relationship existing between two quantities such that the change in one quantity is exactly and directly (linearly) proportional to the change in the other quantity. Note: the quantities and ranges involved must be clearly specified.

LOADING ERROR

The error introduced when more than rated current is drawn from the output of a device.

LOADING NOISE

A noise which occurs in potentiometric transducers when current is drawn from the instrument. It is caused by fluctuating contact resistance between the slider and the wire or film and by the surface of contact between the slip ring and the slip ring contact.

MAGNETIC DAMPING

Damping accomplished through the generation and dissipation of electromagnetic energy.

MEASURAND

A physical quantity, force, property or condition being measured.

NATURAL FREQUENCY

The natural frequencies of an undamped body or system are the frequencies of free oscillations.

NOISE

Any unwanted disturbance or signal which degrades the desired data.

NOMINAL RANGE

See rated range.

NON-LINEARITY

It is preferred that this term not be used. See linearity.

NULL

(Adjective) Pertaining to a condition of balance in a device or system which results in zero output.

(Verb) To oppose an output which differs from zero by a counteraction which returns the output to zero.

OPERATING TEMPERATURE

The range of temperatures, in which a transducer is expected to operate within specified limits of error.

OPTIMAL DAMPING

Damping ratio slightly less than unity which limits the overshoot to a value less than the specified uncertainty of the instrument.

OUTPUT

The electrical signal from a system or device which is a function of the applied stimulus or signal.

PEAK AMPLITUDE

The maximum deviation of a phenomenon from its average or mean position. When applied to vibration, same as single amplitude.

PEAK-TO-PEAK

The maximum algebraic difference between two or more stimuli or signals.

PICKUP

The preferred term is transducer.

PRIMARY CALIBRATION

Calibration in which the transducer output is observed, or recorded, while a direct known stimulus is applied under controlled conditions.

PRIMARY STANDARD

A unit directly defined and established by some authority, against which all secondary standards are calibrated.

RANGE

A statement of the quantitative limits of a physical system.

RATED RANGE

The range within which a device should be operated in order to maintain the performance characteristics specified by its manufacturer.

RATIO CALIBRATION

A method by which potentiometric transducers may be calibrated, in which the value of the measurand is expressed in terms of decimal fractions representing the ratio of output resistance to total resistance.

REACTIVE BALANCE

The capacitive or inductive balance which is often required to null the output of certain transducers or systems when the excitation and/or the output is given in terms of alternating currents.

RELIABILITY

A measure of the probability that a system or device will continue to perform within specified limits of error for a specified length of time under specified conditions.

REPEATABILITY

The ability of a system to repeat a measurement of a fixed stimulus to a specified accuracy.

RESOLUTION

The degree to which small increments of the measurand can be discriminated in terms of instrument output. The smallest change in applied stimulus that will produce a detectable change in the instrument output.

RESOLUTION NOISE

The step wise voltage variations due to the slider moving across discrete turns of the resistance winding in potentiometer type transducers.

RESPONSE (TRANSDUCER)

A quantitative expression of the output of a transducer as a function of the input, under conditions which must be explicitly stated.

RESPONSE TIME

The time required for the output of a transducer to reach 63.7% of the final output when subjected to a step function input of stimulus.

SCALE FACTOR (TRANSDUCER)

The factor by which the number of scale divisions indicated or recorded by a transducer should be multiplied to compute the value of the measurand.

SECONDARY STANDARD

A unit defined and calibrated against a primary standard. See <u>primary standard.</u>

SEISMIC MASS

The element in an accelerometer which is intended to serve as the force-summing member for applied accelerations and/or gravitational forces.

SENSITIVITY

The change in the reading of a measuring instrument per unit of measured quantity.

SENSITIVITY SET

A permanent change in sensitivity attributable to any cause, such as over-ranging, shock, aging, etc.

SENSITIVITY SHIFT

A change in sensitivity from a reference value. That is, change from a response slope previously obtained which is due to any cause.

SENSITIVITY SHIFT WITH TEMPERATURE

The change in sensitivity which is a function of temperature only.

SHOCK

An abrupt change in applied energy.

SHUNT CALIBRATION

A calibration in which a parallel resistance is placed across a like or similar element to obtain a known and deliberate electrical change.

SPEED OF RESPONSE

The preferred term is response time.

STABILITY

The quality of imperviousness to unwanted changes in parameters.

STANDARD

A value or concept that has been established by authority, custom, or agreement, to serve as a model or rule in the measurement of a quantity or in the establishment of a practice or procedure.

STANDARDIZATION

The act or process of reducing something to or comparing it with a standard.

STATIC TEST

A measurement taken under conditions where neither the stimulus nor the environmental conditions fluctuate.

STEP CALIBRATION

A calibration in which the stimulus or substitution of stimulus is applied in discrete increments.

STIMULUS

A cause which produces change.

STORING TEMPERATURE

The range of temperatures at which a transducer may be stored or transported without degradation of performance.

STRAIN

The deformation of a solid resulting from a stress, measured by the ratio of the change to the total value of the dimension in which the change occurred.

STRAIN GAGE, ELECTRIC

A type of transducer used in the telemetering of stresses and strains usually consisting of an element, or group of elements which change their resistivity as a function of applied stresses.

STRESS

The force acting in a unit area of a solid.

SWEPT RESISTANCE

The portion of the total resistance of a potentiometric transducer over which the slider travels when the device is operated throughout its total range.

TANGENT SENSITIVITY

The slope of the line tangent to the response curve at the point being measured.

TEMPERATURE COMPENSATION

Same as thermal compensation.

TEMPERATURE EFFECT

The difference between the output at room temperature and at any other specified temperature at any one value of the stimulus within the range of the measuring device.

TERMINAL-BASED LINEARITY

Same as end-point linearity.

TERMINAL LINEARITY

Same as end-point linearity.

THERMAL COEFFICIENT OF RESISTIVITY

The changes in the resistivity of a substance due to the effects of temperature only. Usually expressed in ohms per ohm per degree change in temperature.

THERMAL COEFFICIENT OF SENSITIVITY

The change in full-scale output due to the effects of temperature only. Usually expressed in percentage of the full scale output at room

temperature per unit, or interval, change in temperature.

THERMAL COMPENSATION

A method employed to reduce or eliminate the thermal effects on one or more of the performance parameters of a transducer.

THERMAL ZERO SHIFT

The change in output, at zero measurand, due to the effects of temperature only. Usually expressed in percentage of full scale output at room temperature per unit, or interval, change in temperature.

THERMISTOR

A resistor whose value varies with temperature in a defininte desired manner.

THERMOCOUPLE

A transducer which depends on the production of an emf in two dissimilar metals as a function of the temperature or temperature change.

THRESHOLD

The point at which an effect is first produced, observable, or otherwise indicated.

THRESHOLD OF SENSITIVITY

The smallest change in stimulus that will result in a detectable change in output.

TRANSDUCER (INSTRUMENTATION)

A device which responds to a phenomenon and produces a signal which is a function of one or more characteristics of the phenomenon.

TRANSDUCER, ALTERNATING CURRENT

A transducer which, for proper operation, must be excited with alternating current only.

TRANSDUCER, BI-DIRECTIONAL

A transducer capable of measuring stimulus in both a positive and a negative direction from a reference zero or rest position.

TRANSDUCER , BONDED

A transducer which employs the bonded strain gage principle of transduction.

TRANSDUCER, CRYSTAL

The preferred term is peizoelectric transducer.

TRANSDUCER, DIFFERENTIAL

A transducer which is capable of simultaneous exposure to two separate stimulus sources and which provides an output proportional to the difference between the stimuli.

TRANSDUCER, DIRECT CURRENT

A transducer capable of proper operation when excited with a source of direct current, and the output of which is also given in terms of direct current unless otherwise modified by the function of the stimulus.

TRANSDUCER, ELECTROCHEMICAL

A transducer which uses a chemical change at the input to generate an electrical output.

TRANSDUCER, FORCE BALANCE

A transducer in which the output from the sensing member is amplified

and fed back to an element which causes the force-summing member to return to a condition of balance. The magnitude of the signal fed back constitutes the output of the device.

TRANSDUCER IONIZATION

A transducer in which the displacement of the force-summing member is sensed by means of induced changes in differential ion conductivity.

TRANSDUCER MAGNETOELECTRIC

A transducer which measures the emf generated by the movement of a conductor relative to a magnetic field.

TRANSDUCER PHOTOELECTRIC

A transducer which converts changes in light energy to changes in electrical energy.

TRANSDUCER , PIEZOELECTRIC

A transducer utilizing a piezoelectric element.

TRANSDUCER POTENTIOMETRIC

A transducer in which transduction is accomplished by the changing ratios of a voltage divider.

TRANSDUCER, SELF-GENERATING

A transducer which provides output signals without external electrical excitation.

TRANSDUCER , SERVO

Same as <u>force balance transducer</u>.

TRANSDUCER, UNI-DIRECTIONAL

A transducer which measures stimulus in only one direction from a reference zero or rest position.

TRANSDUCER, VARIABLE CAPACITANCE

A transducer in which the output is a function of the change in electric capacitance.

TRANSDUCER, VARIABLE INDUCTANCE

A transducer in which the output is a function of the change in a variable inductance element.

TRANSDUCER, VARIABLE RELUCTANCE

A transducer in which the output is a function of the variation in the reluctance of a magnetic circuit.

TRANSDUCER, VARIABLE RESISTANCE

A transducer in which the output is a function of the change in its electrical resistance.

TRANSDUCER, VELOCITY

A transducer which generates an output proportional to velocity.

TRANSVERSE ACCELERATION

The acceleration which is applied in any direction perpendicular to the axis of sensitivity.

TRANSVERSE SENSITIVITY

The ratio of change in output to an incremental change in a given stimulus along any axis perpendicular to the sensitive axis. In accelerometers, it refers to the change in the transducer output at zero acceleration and at some other acceleration value applied along a plane perpendicular to the sensitive axis.

VIBRATION

Motion due to a continuous change in the magnitude of a given force

which reverses its direction with time. Vibration is generally interpreted as symmetrical or non-symmetrical fluctuations in the rate at which acceleration is applied to an object.

VIBRATION EFFECT

The peak instantaneous change in output at a stated vibration level for any stimulus value within the range of the transducer. Usually expressed in percentage of full-scale output per vibratory "g" over a stated frequency range. It may also be specified as a total error in percentage of full-scale output for a stated level of vibration.

VIBRATION SENSITIVITY

The preferred term is vibration effect.

VISCOUS DAMPING

Same as fluid damping.

ZERO ADJUSTMENT

The act of nulling out the output from a system or device. Also, the circuit or means by which a "no output" condition is obtained from an instrument when properly energized.

ZERO BASED LINEARITY

A manner of expressing non-linearity errors as deviations from the most favorable straight line which crosses the instrument output at zero measurand value. The line from which zero based linearity is calculated is also termed best fit straight line with forced zero.

ZERO-COMPENSATION

A method by which transducer output at zero measurand may be minimized and maintained within known limits.

ZERO DRIFT

A change in output at zero measurand attributable to any cause.

APPENDIX III

PHYSICAL EFFECTS AND PRINCIPLES WHICH FORM THE BASIS FOR TRANSDUCTION

TABLE OF CONTENTS

PHYSICAL EFFECTS AND PRINCIPLES WHICH FORM THE BASES FOR TRANSDUCTION (Ref. III-1)

I INTRODUCTION

An awareness of the effects and principles described in the following paragraphs may be of considerable use to transducer design engineers who are searching for new ways to convert measurands to electrical signals suitable as inputs to telemetry systems. The reader's attention is called to a book titled Physical Laws and Effects by C. F. Hix, Jr. and R. P. Alley, published by John Wiley and Sons, Inc., copywright 1958 by General Electric Company. On pages 1 through 4 the authors present some excellent comments and examples concerning previous applications and future possibilities of using physical laws and effects which are generally thought of as being laboratory curiosities.

II PHYSICAL EFFECTS AND PRINCIPLES

a. Edison or Richardson Effect

The thermionic emission of electrons from hot bodies at a rate which increases rapidly with temperature.

b. Galvanomagnetic and Thermomagnetic Effects

(1) Hall Effect

The development of a transverse electric potential gradient in a current-carrying conductor upon the application of a magnetic field (see Section II, Volume I of this handbook).

III-1 Pearlstein, J., Searching the Literature for Transducer Information, Part I " A Guide to the Literature", Diamond Ordnance Fuze Laboratories, Washington, D. C., pp 16-23.

(2) Ettingshausen Effect

If a strip of metal in which an electric current flows longitudinally is placed in a magnetic field with the plane of the strip perpendicular to the direction of the field, it is found that corresponding points on opposite edges come to different temperatures.

(3) Nernst Effect

If heat is flowing through a strip of metal and the strip is placed in a magnetic field perpendicular to its plane, a difference of electric potential develops between the opposite edges.

(4) Righi-Leduc Effect

If heat is flowing through a strip of metal and the strip is placed in a magnetic field perpendicular to its plane, a temperature difference develops across the strip.

c. Thermoelectric Effects

(1) Seebeck Effect

The emf produced in a circuit containing two contacting conductors of different metals having two junctions at different temperatures. This effect may be thought of as the result of two opposing effects; namely, the Thomson emf and the Peltier emf.

(2) Peltier Effect

This is the inverse of the Seebeck effect. When two unlike conductors are joined and kept at a constant temperature while a current passes through the junction, heat is generated or absorbed at the junction (in addition to the I^2R loss).

(3) Thomson Effect

A potential gradient is developed along a homogeneous conductor in which a thermal gradient exists. The inverse effect, the production of heat by the passage of a current, also occurs. This should not be confused with the I^2R loss.

d. Gyromagnetic Effects

Change of magnetization by rotation (Barnett effect) and, inversely, change of rotation by magnetization (Einstein DeHaas effect).

e. Piezoelectric Effect

The interaction between electrical and mechanical stress-strain variables in certain materials. Thus, compression of a crystal of quartz or Rochelle salt generates an electrostatic voltage across it, and, conversely, application of an electric field may cause the crystal to expand or contract in certain directions. Piezoelectricity is only possible in crystals which do not possess a center of symmetry. Unlike electrostriction, piezoelectric deformations are directly proportional to the electric field (as long as the crystal is outside the ferroelectric region) and reverse their sign upon reversal of field.

f. Ferroelectric Effect

So far as macroscopic observations are concerned, a ferroelectric crystal (seignette-electric) may be defined as having a critical temperature (Curie Point) on one side of which the dielectric properties exhibit nonlinearity and hysteresis (the ferroelectric region) while on the other side there is no hysteresis and the relation between polarization and field is nearly or quite linear. In the case of certain crystals, e.g., barium titanate, which become centrosymmetrical, the piezoelectric properties disappear above the Curie point. Ferroelectric crystals (except those which become centrosymmetrical above the Curie point) are piezoelectric on both sides of the Curie point.

g. Electrostrictive Effect

All dielectrics, whether gaseous, liquid, or solid, when placed in an electric field undergo a deformation which is independent of the direction of the field and proportional to the square of the field. The effect is so minute that, although it is always present in piezoelectric phenomena, it can usually be ignored. Only in fields stronger than 20,000 volts/cm can it be comparable with the effects of piezoelectricity.

h. Magnetostrictive Effects

(1) Joule Effect

The change in length of a ferromagnetic material subjected to an increasing or decreasing longitudinal magnetic field.

(2) Villari Effect

A change of magnetic induction within a ferromagnetic material under longitudinal stress (inverse Joule Effect).

(3) Wertheim Effect

The development of a transient voltage between the ends of a wire which is twisted in a longitudinal magnetic field.

(4) Wiedemann Effect

The twisting of a rod carrying an electric current when subjected to a longitudinal magnetic field. The Inverse Wiedemann Effect is the axial magnetization of a current-carrying wire subjected to twisting.

i. Magnetoresistive Effect

The electrical resistance of a metal or semi-conductor is altered by the presence of a magnetic field.

j. Thermoresistive Effect

The change in electrical resistivity of a metal or semi-conductor as a function of temperature. This change in resistivity (resistance of a centimeter cube) is due to the change in some property of a material subjected to a temperature change; that is, the material has a temperature coefficient (positive for most metals, negative for certain semiconducting materials, e.g., thermistors) of resistivity. Since the application of heat to a conductor also changes its dimensions, the net change in resistance of a conductor is the combined effect of the temperature-dependent resistivity and dimensional changes.

k. Mechanoresistive Effects

(1) The change in electrical resistivity of a semiconductor as a function of applied stress; that is, the material has a stress (or strain) coefficient of resistivity. Analogous to that of a thermoresistive element, the net change in resistance of a strain-sensitive element is the combined effect of a stress-produced change in resistivity (property) and change in dimensions.

(2) The change in ohmic resistance of an electric element by movement of contacts (changing either effective area or length of resistance element). The movement of the contacts can be produced by linear or angular displacement, by applied pressure, etc.

(3) Variation of the transconductance or the plate resistance of a vacuum tube by movement of one or more of the elements.

l. Electroresistive Effect

The change in resistivity of a material as a result of a change in applied voltage. The Varistor (essentially silicon carbide with metallic contacts) is an electroresistive material with a nonlinear resistance-voltage characteristic.

m. Mechano-Capacitive Effects

Variation of electrical capacitance of a capacitor by any one or any combination of the following:

(1) Change in separation of the plates.

(2) Change in area of the plates.

(3) Change in the dielectric constant of the dielectric.

In the reverse effect, a change in the charge on a capacitor causes movement or distortion of its plates.

n. Variable Inductance Principle

The change in inductance of an inductor as the result of relative displacement of its elements (core position, armature position with respect to core, i.e., variable air gap, or the change in effective inductive reactance of a coil as the result of a change in mutual inductance between it and another circuit. The mutual inductance of a pair of coils can be changed by changing the distance between them or their relative orientation, or altering the length, cross-sectional area, or magnetic permeability of an iron core coupling the coils.

o. Generator Principle

The development of an emf as the result of relative motion between a conductor and a magnetic field.

p. Proximity Effect

The change in current distribution (with the related changes in resistance and capacitance) in a conductor due to the field produced by an adjacent conductor.

q. Pyroelectric Effects

(1) The separation of electric charge in a crystal by heating.

(2) The converse, or electrocaloric effect is the change in termperature of a pyroelectric crystal caused by a change in the electric field.

r. Triboelectric Effect

The separation of electric charges by friction between bodies.

s. Volta or Contact-Potential Effect

The development of opposite electrical charges on two dissimilar uncharged metals when placed in contact.

t. Luminescent Effects

The emission of light due to any other cause than high temperature.

(1) Triboluminescence

Light emission due to rubbing or grinding certain solids, usually crystalline materials.

(2) Thermoiuminescence

Light emission due to heating certain substances (such as diamond, marble, and fluorite) at temperature below a red heat.

(3) Chemiluminescence

Light emission due to chemical action.

(4) Cathodoluminescence

Light emission due to excitation by fast electrons.

(5) Electroluminescence

Ligh' emission due to excitation by strong alternating electric fields.

(6) Photoluminescence

Light emission due to excitation of certain crystals by optical radiation (e.g., ultraviolet light, X-rays).

If the time between the introduction of excitation energy and the emission of light is very short ($< 10^{-8}$ sec), the phenomenon is usually called fluorescence; if the time is longer, it is usually called phosphorescence and the crystals exhibiting this phenomenon are called phosphors.

u. Photoconductive Effect

The change (usually increase) in conductivity of certain crystals under the action of light. In general terms, the light excites electrons into the conduction band where they can move freely, and carry a current.

v. Photoelectric Effect (Photoemissive Effect)

The liberation of electrons from a surface when light falls upon it. In this effect, radiation of sufficiently high frequency, impinging on certain substances, particularly, but not exclusively, metals, causes bound electrons to be given off with a maximum velocity proportional to the frequency of the radiation, i. e., to the entire energy of the photon.

w. Photovoltaic Effect

The production of an electromotive force by incidence of radiant energy, commonly light, upon the junction of two dissimilar materials, such as a p-n junction of metal-semiconductor junction.

x. Electro-Optic Effect

The alteration of the refractive properties of an optical medium by the application of a strong electric field. In a liquid medium the effect is designated as the Kerr effect and in a piezoelectric crystalline medium it is known as the Pockels effect.

y. Faraday Effect

The rotation of the plane of polarization produced when plane polarized light or microwave energy is passed through a substance in a magnetic field, the radiation traveling in a direction parallel to the field.

z. Photoelastic Effect

The change in the optical properties of isotropic, transparent dielectrics when subjected to stress. For example, a block of glass, free from optical flaws, exhibits "forced" double refraction when put under compression or tension parallel to one of its dimensions.

aa. Photo-Electromagnetic (Photo-Magnetoelectric) Effect

When a slab of a semiconductor, placed in a magnetic field, is illuminated in a direction at right angles to the field, a voltage is developed in the mutually perpendicular direction.

bb. Photo-Thermoelectric (Thermal-Photoelectric) Effect

The development of an electromotive force in a semi conductor carrying a thermal current when exposed to light.

cc. Electrokinetic Effects

There are four phenomena involving the electrical forces set up by the relative motion of solids and liquids and such relative motions set up by electromotive forces.

(1) Electroosmosis

An applied emf causes a liquid to move along the stationary walls of a tube.

(2) Electrophoresis

An applied emf causes solid particles to move through stationary liquids.

(3) Stream or Flow Potentials

The production of an emf by the motion of a liquid through stationary tubes.

(4) Dorn Effect

The production of an emf by the motion of solid particles through liquids.

dd. Galvanic (Electrochemical) Effects

The production of electrical energy by chemical action (including changes in ion concentration at electrodes, i. e, changes in

current flow as a function of concentration polarization) and inversely, the production of chemical change through electrolysis, i. e., the conversion of electrical energy into chemical energy by transfer of electrons and ions and recombinations of electrical charge.

ee. Photochemical Effect

The initiation of chemical reaction by the absorption of light.

ff. Additional Thermal Effects

All materials and devices are affected by temperature in one way or another. In most measurements temperature must be controlled, compensated, or otherwise taken into consideration to minimize errors in measurement of the primary physical quantity. A number of effects which serve as bases for temperature measurement have been listed above. Additional effects which may be utilized for temperature measurement are given below:

(1) The change in spectral radiation from a body as a function of temperature.

(2) The displacement or change in size of a body as a function of temperature (temperature coefficient of expansion or differential coefficient of expansion).

(3) The change in pressure of a confined gas or vapor as a function of temperature (gas laws).

(4) The melting, softening (e. g., of pyrometric cones), or vaporization of materials at fixed temperatures.

(5) The relation between the amount of ionization in gases and temperature (above 4,000°C).

(6) The change in magnetic susceptibility of certain paramagentic materials with temperature. (This effect can be used to measure temperature below 4°K.)

(7) The change in color of temperature-sensitive paints. A certain amount of time, several minutes at the appropriate temperature, is required for the change. At least one paint works on the dehydration principle, and gives a reversible indication. That is, the color change is reversed on cooling again. Other paints undergo a permanent chemical change. The same paint may pass through a gradual change involving several distinguishable colors, and so can give indications of more than one temperature. One firm (The Tempil Corporation) supplies 16 different types, which indicate temperature from 175° to 1470°F.

gg. Effects Involving Radiation from Radioactive Sources as a Medium

Four types of radiation emitted by radioactive materials are alpha, beta, and gamma rays, and neutrons. Many of the effects involving light and charged particles as transducing media, similar to those listed above, are exhibited when the radiation from radioactive materials is used as the transducing medium. The properties of this radiation that are utilized in measurements are: its penetrability; capacity to be absorbed, reflected, refracted, and diffracted; ionization power; and ability to induce radioactivity in certain materials from which measurement are desired. The principal transducers used for detection and measurement of the radiation are phosphors, photographic film, Geiger-Mueller tubes, scintillation counters, and ionization chambers.

hh. Mechanical Displacement and Strain Effects

In this category are included all displacements and dimensional changes of bodies (or devices) that occur in response to various mechanical quantities, e.g., pressure, torque, acceleration, velocity, momentum, kinetic energy. The more important principles governing the operation of mechanical transducers are the following:

(1) Newton's laws of motion and gravitational attraction.

(2) The law of conservation of energy.

(3) The law of conservation of linear and angular momentum. The operation of a gyroscope as an instrument for measuring and controlling displacement, velocity, direction, etc., is primarily based on the law of conservation of angular momentum.

(4) Hooke's law (In an elastic material, strain is proportional to stress).

(5) The lever principle.

(6) Static equilibrium principles (Parallelogram principle, force polygon, etc.).

(7) Bernoulli's theorem.

(8) Archimedes' principle.

(9) Pascal's law.

APPENDIX IV

1. ACCELEROMETER FUNDAMENTALS (Ref. IV-1)

Figure IV-1 shows a schematic of a fundamental linear accelerometer in which a mass is suspended from the accelerometer case by means of a spring. Damping is accomplished by either mechanical or electrical means and the case is mounted rigidly to the device whose acceleration is desired. The relationship between acceleration of the case and motion of the mass may now be developed.

X = displacement of accelerometer case in space, cm
Y = displacement of accelerometer mass with respect to the case, cm
a = acceleration of accelerometer case in space, cm/sec^2
M = acceleration-sensitive mass (sometimes called seismic mass), gm
B = damping, dynes/cm/sec
K = spring constant, dynes/cm

Units given above are representative only, and in developing the equations the operator p will be used to denote the derivative of a quantity. The basic equation of motion of the accelerometer indicates that the force to accelerate the seismic mass comes from the damping and the spring.

$$Mp^2 (X-Y) = BpY + KY \tag{1-1}$$

$$Mp^2 X = Mp^2 Y + BpY + KY$$

$$\frac{Y}{p^2X} = \frac{M/K}{\frac{M}{K}p^2 + \frac{B}{K}p + 1} \tag{1-2}$$

But $p^2 = a$. Therefore, the transfer function (Ref. IV-2) seismic mass displacement to case acceleration is:

$$\frac{Y}{a} = \frac{M/K}{\frac{M}{K}p^2 + \frac{B}{K}p + 1} \tag{1-3}$$

IV-1 Same as Reference 179

Ref. IV-2 Ritow, Ira "Automatic Control System Design--3, Frequency Response and Transfer Functions," Electrical Manufacturing, June 1959, p. 129

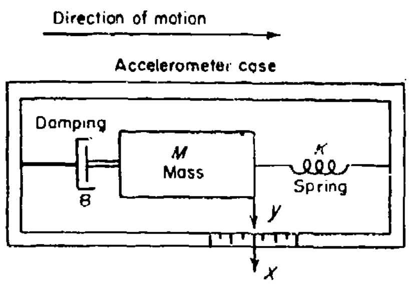


Fig. IV-1 Fundamental linear accelerometer.

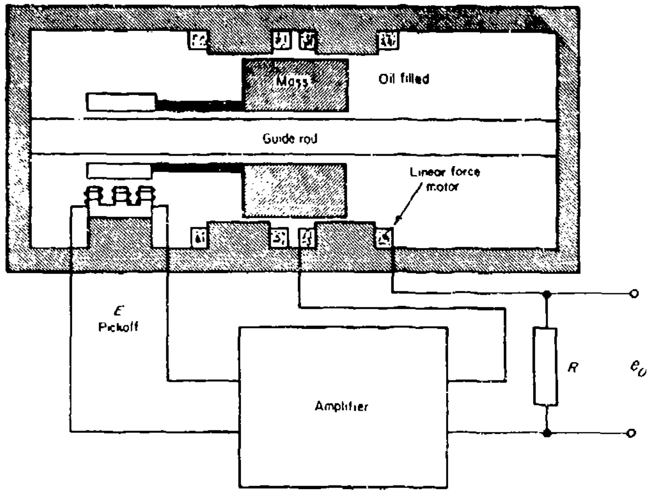


Fig. IV-2 Accelerometer with mass floated in oil to minimize driction and prevent mass from being forced against guide rod by accelerations along axes other than the sensitive one.

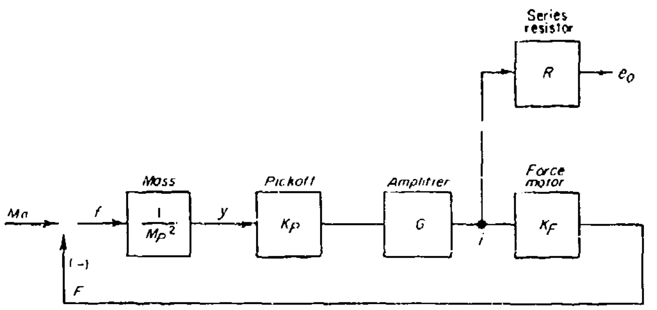


Fig. IV-3 Block diagram of accelerometer shown in Fig. IV-2.

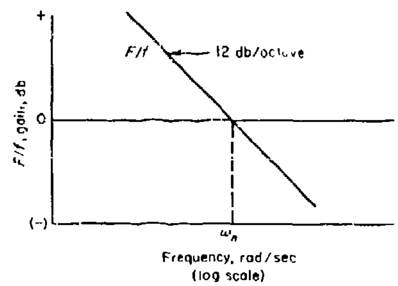
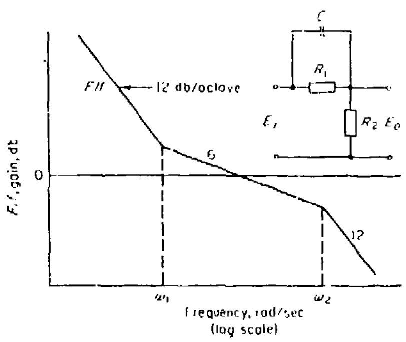


Fig. IV-4 Bode diagram of system in Fig. IV-3.



$$\frac{E_o}{E_i} = \frac{R_2\left(1+p\frac{1}{\omega_1}\right)}{R_1+R_2\left(1+p\frac{1}{\omega_2}\right)}$$

$$\frac{1}{\omega_1} = R_1C \qquad \frac{1}{\omega_2} = \frac{R_2(R_1C)}{R_1+R_2}$$

Fig. IV-5 Bode diagram of system in Fig. IV-3 with lead-lag network added to improve stability.

This is the classic transfer-function equation for a spring-mass system. The ratio of mass to spring constant gives the steady-state displacement of the system to unit acceleration. In addition, the denominator of the expression may be rewritten as follows:

$$\left(\frac{1}{W_n}\right)^2 p^2 + 2Z \frac{1}{W_n} p + 1 \tag{1-4}$$

where

W_n = undamped natural or resonant frequency, rad per sec
Z = damping constant

When Z is unity, the accelerometer is critically damped and the denominator is factorable into a pair of repeated roots. If Z is less than unity, the accelerometer is under damped and the factors of the quadratic are complex. Damping of slightly less than unity is quite common. If Z is greater than unity, the quadratic is factorable into two real roots.

Figure IV-2 shows a more sophisticated version of fundamental accelerometer. The equations of motion of this device may be written:

$$Mp^2 (X - Y) = Bp\, Y + KY$$

which is the same as Eq (1-1). Additional parameters are:

K_F = motor force constant, dynes per milliamp
u = amplifier gain, milliamp per volt
K_p = pickoff gain, volts per cm
R = resistance in series with motor, ohms x 10^3
i = current in force motor, milliamps
e_o = accelerometer output, volts

Since the spring constant now is the product of the pickoff, amplifier and force motor gains:

$$K = K_F u K_p \tag{1-5}$$

Also:

$$i = \frac{e_o}{R} \tag{1-6}$$

$$i = YK_p u \tag{1-7}$$

Substituting Eq (1-6) into Eq (1-7) and solving for Y,

$$Y = \frac{e_o}{K_p u R} \tag{1-8}$$

If Eqs (1-5) and (1-8) are now substituted into Eq (1-1) and solved, the transfer function relating output voltage to acceleration is as follows:

$$\frac{e_o}{a} = \frac{MR/K_F}{\left(\frac{M}{K_F u\, K_p}\right) p^2 + \left(\frac{B}{K_F u\, K_p}\right) p + 1} \tag{1-9}$$

Again looking at Fig. IV-2 and assuming that no damping is present in the unit, the following equation may be written in regard to the mass:

$$F = Mp^2 (X - Y) \tag{1-10}$$

where F = force in dynes. Solving for Y,

$$Y = \frac{1}{Mp^2} (Mp^2 X - F) \tag{1-11}$$

Since X = input acceleration a,

$$Y = \frac{1}{Mp^2} (Ma - F) \tag{1-12}$$

A block diagram may now be drawn of the accelerometer without internal damping as shown in Fig. IV-3 where

G = complete amplifier transfer function

f = the force error of the system (which exists only when acceleration is changing)

Equation (1-12) is represented by the mass transfer function and its inputs (Ma--F). A study of the servo open-loop transfer function F/f indicates that if gain is used only in the amplifier, the system will have no damping and will be unsatisfactory. A Bode diagram plot of the open-loop transfer function, as in Fig. IV-4 indicates a 0 db axis crossover of 12 db per octave and 0 degree phase margin. Practically, the system will oscillate due to other time constants in the system which normally can be ignored. However, the addition of a lead-lag network to the

amplifier will provide a satisfactory system, as indicated in Fig. IV-5. It will be necessary to raise the gain of the amplifier to compensate for the loss of gain in the network. The closed-loop transfer function of this system relating output voltage as a function of acceleration is:

$$\frac{e_o}{a} = \frac{MR\left(1 + p\,\frac{1}{W_1}\right)}{K_f\left[p^3\,\frac{1}{K_c W_2} + p^2\,\frac{1}{K_c} + p\,\frac{1}{W_1} + 1\right]} \qquad (1\text{-}13)$$

where

$$K_c = \frac{K_p \quad G_a \quad K_f}{M}$$

G_a = product of amplifier gain and gain loss in lead-lag network, milliamps per volt

W_1 = frequency, rad/sec, at which lead time constant $1/W_1$ occurs

W_2 = frequency, rad/sec, at which lag time constant $1/W_2$ occurs

The frequencies W_1 and W_2 are chosen to be respectively above and below the 0 db axis and classical servo synthesizing methods may be used to give the required performance.

Another class of instrument is represented by the pendulous type of accelerometer shown schematically in Fig. 2-103 where

K = spring constant, dyne-cm/rad

B = damping, dyne-cm/rad/sec

l = length of simple pendulum, cm

M = mass of pendulum, grams

α = angle of pendulum with respect to case, rad

X = linear displacement of case in space, cm

Y = linear displacement of pendulum mass with respect to case, cm

a = acceleration of accelerometer case in space, cm/sec^2

In this instrument a pendulum is suspended on an axis so that it is free to move through an angle with respect to the accelerometer case. Damping again is accomplished by either mechanical or electrical means and the pendulum is restrained by a torsion spring. In developing the equations of motion for the simple pendulum, it is assumed that the angle the pendulum makes with the case remains small. The basic equation of motion is very similar to Eq (1-1):

$$Mp^2 (X - Y) l = Bp\alpha + K\alpha \qquad (1\text{-}14)$$

For small angles, Y = la. Substituting this into Eq (1-14) and solving:

$$\frac{a}{p^2 X} = \frac{Ml/K}{\frac{Ml^2}{K} p^2 + \frac{B}{K} p + 1} \qquad (1\text{-}15)$$

Since $p^2 X = a$, the transfer function relating angular motion of the pendulum to case acceleration is:

$$\frac{\alpha}{a} = \frac{Ml/K}{\frac{Ml^2}{K} p^2 + \frac{B}{K} p + 1} \qquad (1\text{-}16)$$

The numerator of the expression gives the steady-state angular displacement of the system to unit acceleration. The denominator of the expression may also be replaced by Eq (1-4) where

$$W_n = \left(\frac{K}{Ml^2}\right)^{1/2}$$

$$Z = \frac{W_n B}{2K}$$

Fig. 2-104 shows accelerometer with compound pendulum. Using

l = length of unbalance mass from center of rotation, cm

M = the unbalance mass concentrated at its center of gravity, gm

J = inertia of the balanced mass about the center of rotation, gm-cm^2 the equation of motion can be written:

$$Mp^2 (X - Y) l = J_o p^2 \quad + \ Bp \quad + \ K$$

Again, for small angles, $Y = la$. Also, acceleration $a = p^2 X$. The transfer function relating angle of rotation of pendulum to linear acceleration becomes:

$$\frac{\alpha}{a} = \frac{Ml/K}{\frac{Ml^2 + J_o}{K} p^2 + \frac{B}{K} p + 1} \qquad (1\text{-}17)$$

Thus, the undamped natural frequency is determined by the square root of the ratio of spring constant to inertia of the compound pendulum about its axis of rotation. Angle of rotation for steady-state acceleration is determined by the total pendulum mass and the length of the center of gravity from center of rotation, the product of the two quantities being divided by the spring constant.

The pendulous accelerometer of Figure IV-6 represents one of the more complex (although highly accurate) devices that may be used. It consists of the conventional single-axis, floated, damped HIG gyro modified so that the gyro gimbal is unbalanced by a known amount. A servo amplifier accepts the error from the gyro signal generator and, by means of a servo motor, drives the gyro about its input axis to null the signal generator output. The following terminology will be used:

SA = spin axis of gyro wheel
OA = output axis of gyro
IA = gyro input axis (perpendicular to plane containing SA and OA)
α = angle of gimbal about OA, rad
θ = angle of gyro input axis, rad
N = $p\theta$ = angular velocity of servo motor, rad/sec
SG = signal generator on output axis
M = unbalance mass on gimbal, gm
l = moment arm to unbalance mass, cm
I = gyro wheel inertia about SA, gm-cm^2
Ω = gyro wheel velocity about spin axis, rad/sec
$(I\Omega)$ = gyro wheel momentum, gm-cm^2/sec
B = damping about OA, dyne-cm-sec
J_o = gyro gimbal inertia about OA, gm-cm^2
Jm = inertia of complete accelerometer about motor axis rotation (same as IA) gm-cm^2
Ksg = signal generator gain, volt/rad
R = motor armature circuit resistance, ohm
Kt = motor torque constant, dyne-cm/amp
Kv = motor back-emf constant, volt/rad/sec

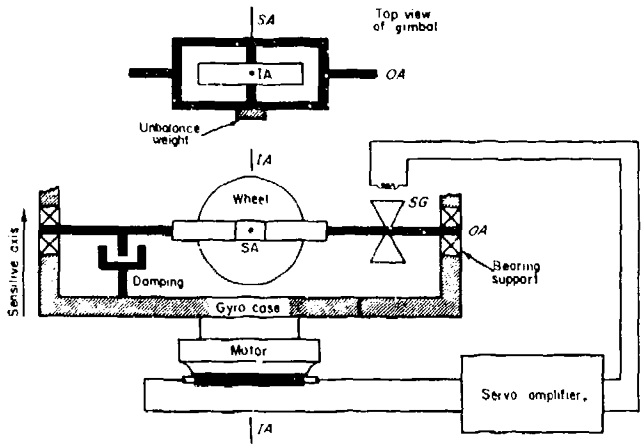


Fig. IV-6 Highly accurate pendulous gyro accelerometer including servo.

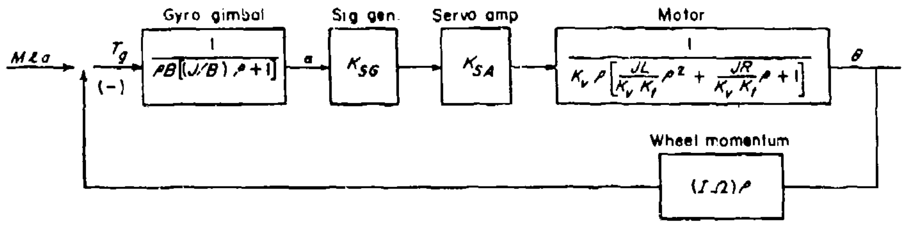


Fig. IV-7 Block diagram of accelerometer in Fig. IV-6.

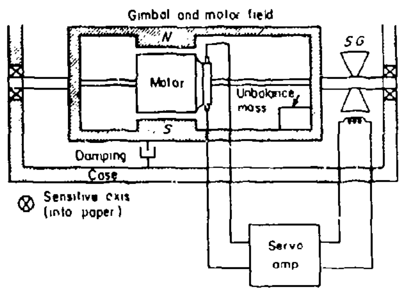


Fig. IV-8 Accelerometer with motor built into pendulum.

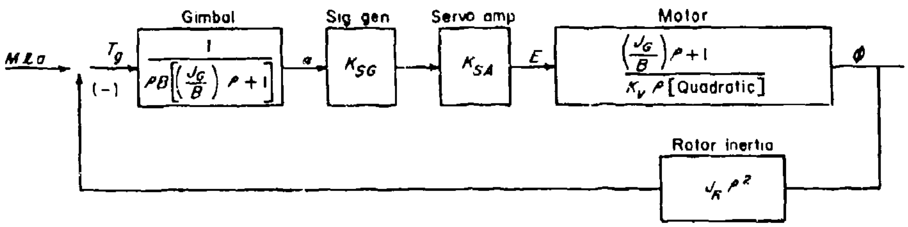


Fig. IV-9 Block diagram of accelerometer in Fig. IV-8.

L = motor armature inductance, henrys
K_{sa} = servo amplifier transfer function
T = torque, dyne-cm
T_g = torque about gimbal OA, dyne-cm
a = linear acceleration along sensitive axis, cm/sec^2

To find the transfer function of the gimbal within the gyro, the torque applied about the output axis may be equated to the sum of the torques to accelerate the gimbal inertia and overcome the damping:

$$T_g = Jp^2\alpha + Bp\alpha \qquad (1\text{-}18)$$

Solving for the transfer function,

$$\frac{\alpha}{T_g} = \frac{1}{pB\left[\left(\frac{J}{B}\right) p + 1\right]} \qquad (1\text{-}19)$$

The ratio of gimbal inertia to damping is sometimes called the characteristic time constant. A high-quality gyro will have small inertia and heavy damping to give a characteristic time constant of 6 millisec or less.

The torque applied to the gyro gimbal comes from the pendulous effects when the device is accelerated along its sensitive axis. Thus the gimbal transfers the torque from linear acceleration into a small angle about the output axis. The signal generator converts the angle into an electrical error signal which is operated upon in the servo amplifier. The servo motor then rotates at the required angular velocity so that the torque developed through the action of the wheel momentum balances the torque caused by linear acceleration. A block diagram of this loop is shown in Figure IV-7.

Most textbooks on physics or mechanics derive the basic gyro equation that converts angular rate about the input axis to a torque about the output axis through the medium of gyro-wheel momentum. The block for the motor gives the transfer function of a d-c motor whose derivation also is available elsewhere. The servo may be stabilized by classical techniques. A further inspection of the system reveals that the angular velocity of the motor is directly proportional to linear acceleration of the device along the sensitive axis. A complete closed-loop analysis indicates that:

$$\frac{N}{a} = \frac{Ml}{I\Omega}\left(\frac{\theta}{D}\right) \qquad (1\text{-}20)$$

where θ/D = closed-loop transfer function of servo, regarding it as a position servo controlling motor angle θ. Its steady state gain is unity.

Because the accelerometer is pendulous, the gain of the servo must be high in order to keep cross talk within acceptable limits. Also, since motor angular velocity is proportional to linear acceleration, it follows that the motor's angular position is proportional to linear velocity. Thus the device is a self-integrating accelerometer and desired output may be obtained by use of an appropriate pickoff.

An accelerometer which used a motor in a rather interesting way is shown in Figure IV-8. A gimbal is supported in bearings within the accelerometer case and a signal generator is present to convert the mechanical error into an electrical signal. The gimbal also is pendulous and supports the stator of a motor. The rotor of the motor is free to turn within the gimbal and torque to restrain gimbal motion is transferred across the motor air gap when the servo amplifier receives an error from the signal generator. The following terminology will be used (already-defined terms which apply are not repeated):

α = position of gimbal with respect to case, rad
ϕ = position of motor rotor with respect to outer accelerometer case, rad
J_g = gimbal plus stator inertia about axis of rotation, gm-cm^2
J_R = inertia of motor rotor, gm-cm^2
i = motor armature current, amp
E = voltage applied to motor armature, volts

The block diagram of the accelerometer is given in Figure IV-9 and contains the same gimbal transfer function as previously developed for the system of Figure IV-7. In finding the transfer function for the motor, the armature circuit inductance is neglected and the basic equation written:

$$E = iR + K_V p\,(\alpha - \phi) \tag{1-21}$$

The torque developed in the motor is equal to the product of the current and the torque constant which, when solved for current, is

$$i = \frac{T}{K_t} \tag{1-22}$$

This same torque, developed across the air gap, accelerates the rotor inertia and also overcomes the gimbal inertia and damping:

$$T = J_R p^2 \phi = J_g p^2 \alpha + Bp\alpha \tag{1-23}$$

Equation (1-23) when solved for a becomes:

$$\propto = \frac{J_R p^2 \phi}{J_g p + B} \tag{1-24}$$

Equation (1-24) and the first part of Eq (1-23) may now be substituted into Eq (1-21) with help of Eq (1-22) to product the motor transfer function:

$$\frac{\phi}{E} = \frac{(J_g/B)(p) + 1}{K_v p \left[\frac{J_R\, J_g\, R}{K_t\, K_v\, B}\, p^2 + \left(\frac{J_R\, R}{K_t\, K_v} + \frac{J_R + J_g}{B} \right) p + 1 \right]} \tag{1-25}$$

The torque which is compared with the input-order signal torque is also expressed by the first part of Eq (1-23) and the block diagram is completed.

If time constants are ignored and the servo gain ϕ/T_g is represented by the constant G, the closed-loop transfer function may be written:

$$\frac{\phi}{Mla} = \frac{G/p^2}{1 + \left(\frac{G}{p^2}\right)(J_R\, p^2)} = \frac{G}{p^2\ (1 + G\, J_R)} \tag{1-26}$$

Solving for transfer function relating angular acceleration of motor to linear acceleration input:

$$\frac{p^2\phi}{a} = \frac{MlG}{1 + GJ_R} \tag{1-27}$$

If the servo gain is large:

$$\frac{p^2\phi}{a} \approx \frac{Ml}{J_R} \tag{1-28}$$

Thus the angular acceleration of the motor is proportional to the linear acceleration of the device along its sensitive axis. Furthermore, angular velocity of the motor is proportional to linear velocity of the device, and angular position of the motor is proportional to the linear distance the device has travelled. This instrument may now be called a double-integrating accelerometer and velocity or position information may be directly acquired if the proper pickoff device is selected.

2. TEMPERATURE MEASUREMENT FUNDAMENTALS (Ref. IV-3)

a. Semiconductors

In an isolated atom, the potential energy of an electron as a function of distance from the positive nucleus 44 can be seen in Fig. 4-10. The point of zero energy is at the nucleus, and the energy increases as an electron is moved away from this point.

Quantum theory states that an electron can have only certain permissible orbits and therefore only certain permissible energy levels. In a metal or other crystalline solid, there is an interaction between adjacent molecules resulting in the energy level diagram shown in Figure IV-11. The Pauli Exclusion Principle infers that no two electrons can have the same energy. Therefore, as atoms combine to form a lattice structure, their electronic orbits tend to over, bringing together electrons with similar energy levels to form continuous bands of permissible energies in a solid.

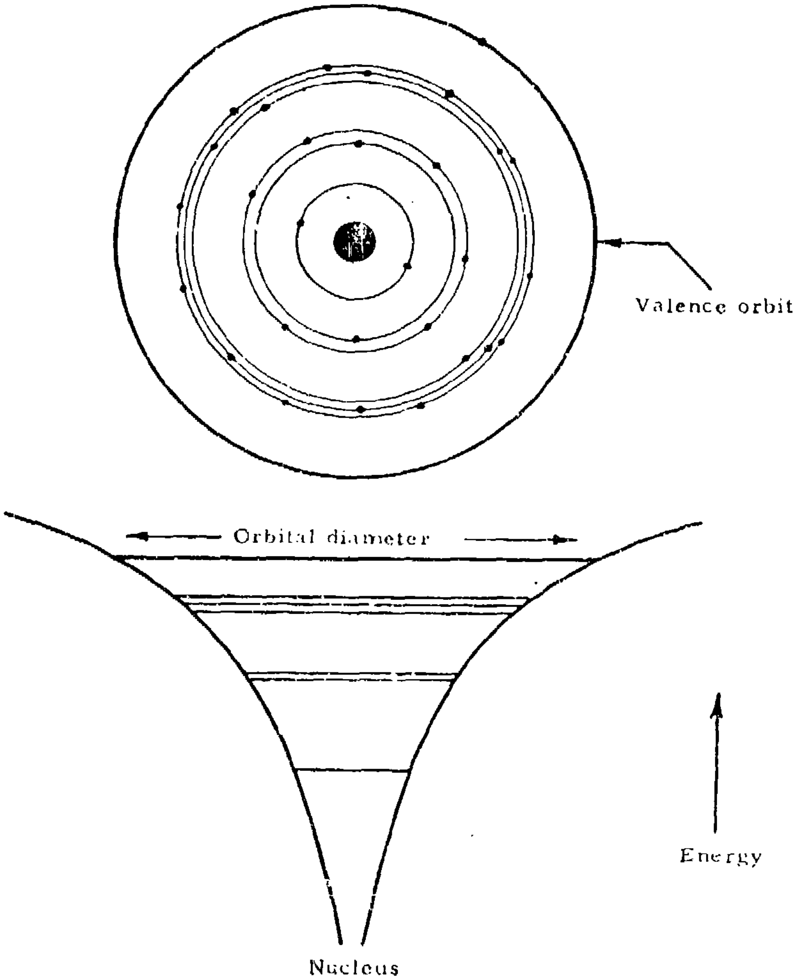
In a good insulator, the valence band as in Figure IV-11 is completely filled and the forbidden energy gap is large enough to prevent thermal excitation of the valence electrons into the unfilled conduction band. Since there are essentially no vacancies (holes) for electrons to occupy, electron travel through an insulator is at a minimum.

A material is a good conductor if either its valence band is unfilled or if the conduction and valence bands overlap. With this arrangement, electrons are free to move to holes within the unfilled valence band, or if the valence band is filled, electrons are able to move to holes in the conduction band.

A semiconductor is a material whose valence band is filled and has a forbidden energy gap intermediate between that of a conductor and an insulator. In intrinsic semiconduction, the energy gap is sufficiently small so that electrons from the valence band can be thermally excited across it. In extrinsic semiconduction, impurity atoms are added to a substance to produce new energy levels within the forbidden energy gap. A P-type semiconductor is one which has an electron accepting energy level slightly above the valence band. An N-type semiconductor is one which has an electron donating energy level slightly below the conduction band. These various energy level configurations are illustrated in Figure IV-12.

Ref. IV-3 Same as Ref. 180

(a) Structure of an atom



(b) Energy levels of orbital electrons in a free atom

Fig. IV-10 Energy Levels of Electronis in an Atom

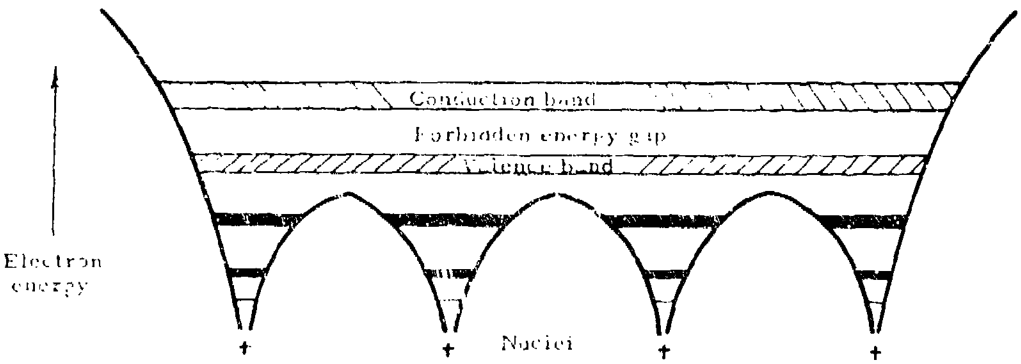


Fig. IV-11 Energy Bands in a Solid

The conductivity in an intrinsic semiconductor is given by the following equation:

$$T = e\, n_e\, u_e + e\, n_n\, u_n \qquad (2\text{-}1)$$

where:

T = Conductivity
e = Electronic charge
n_e = Electron Concentration
n_n = Hole Concentration
u_e = Hole Mobility

Mobility = Velocity/Electric Field
Upon heating, the electron and hole mobilities decreases slightly due to an increase in collisions with thermally agitated molecules. Both u_e and u_n are proportional to $T^{-3/2}$.

This decrease in conductivity with rising temperature is completely offset by a very large increase in electron concentration in the conduction band, and hole concentration in the valence band, owing to electron excitation across the energy gap. As might be expected there is a mathematical relationship between the temperature of a semiconductor and its conductivity. It is derived below gy means of Fermi-Dirac statistics. Much of the development is shown graphically in figures.

By methods of wave mechanics, the following equation can be realized which gives the number of electrons per unit volume that have energies below an arbitrary energy level E at 0° K:

$$n_e = \frac{8\pi\,(2m)^{3/2}}{3h^3}\,E^{3/2} \qquad (2\text{-}2)$$

where

n_e = Electron concentration

m = Electron mass

h = Planck's Constant

E = Energy level

By differentiating the above equation, the number of electrons per unit volume having energies from E to dE is found to be

$$dn_e = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} \, dE \qquad (2\text{-}3)$$

The Fermi-Dirac distribution function shows the probability of electrons occupying higher energy levels at temperatures above 0°K.

$$f(E) = \frac{1}{e^{\left(\frac{E - E_F}{kT}\right)} + 1} \qquad (2\text{-}4)$$

where

E_F = Fermi level

k = Boltzmann's constant

T = absolute temperature

e = 2.732

Under normal conditions $e^{(E - E_F)/kT}$ is much greater than one. The distribution function can, therefore, be written as

$$f(E) = e^{(E_F - E)/kT} \qquad (2\text{-}5)$$

The following equation will give the concentration of free electrons in the conduction band for any temperature.

$$n_e = \int_{E_c}^{\infty} \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} e^{(E_F - E)/kT} dE \qquad (2\text{-}6)$$

E_c in the above equation is the lowest energy level in the conduction band. By letting Ec represent a reference level, it is possible to integrate from zero to infinity by using the Gamma Function of 3/2. This results in Eq (-7)

$$n_e = \frac{(4\pi m\, kT)^{3/2}}{h^2} e^{-(E_C - E_F)/kT} \qquad (2\text{-}7)$$

A similar method shows the concentration of holes in the valence band to be

$$n_n = \frac{(4\pi\, m\, kT)^{3/2}}{h^2} e^{(E_c - E_F)/kT} \qquad (2\text{-}8)$$

By assuming the concentration of holes in the valence band to be equal to the concentration of electrons in the conduction band. the Fermi level must fall midway between the limits of the energy gap (see Figure IV-13). The final equations for the hole and electron concentrations are then

$$n_e = n_n \quad \frac{(4\pi m\, kT)^{3/2}}{h^2} \epsilon^{-\Delta E/2kT} \qquad (2\text{-}9)$$

ΔE = width of energy gap

Since the conductivity of a semiconductor is dependent upon the product of its electron and hole concentration and their respective mobilities, the $T^{3/2}$ factor cancels out and the conductivity varies as $e^{-\Delta E/2kT}$. Similar results hold for extrinsic semiconductors.

The results of this discussion indicate that an increase in temperature would increase the conductivity of a semiconductor and vice versa. Semiconductors are therefore said to possess positive temperature coefficients of conductivity or conversely, negative temperature coefficients of resistivity.

b. Thermionic Emission

The difference between the energy required to overcome the barrier E_a and the Fermi energy level E_F, discussed in section a in connection with semiconduction, is called the work function of the metal. From equations (2-3) and (2-4) of section a, the number of

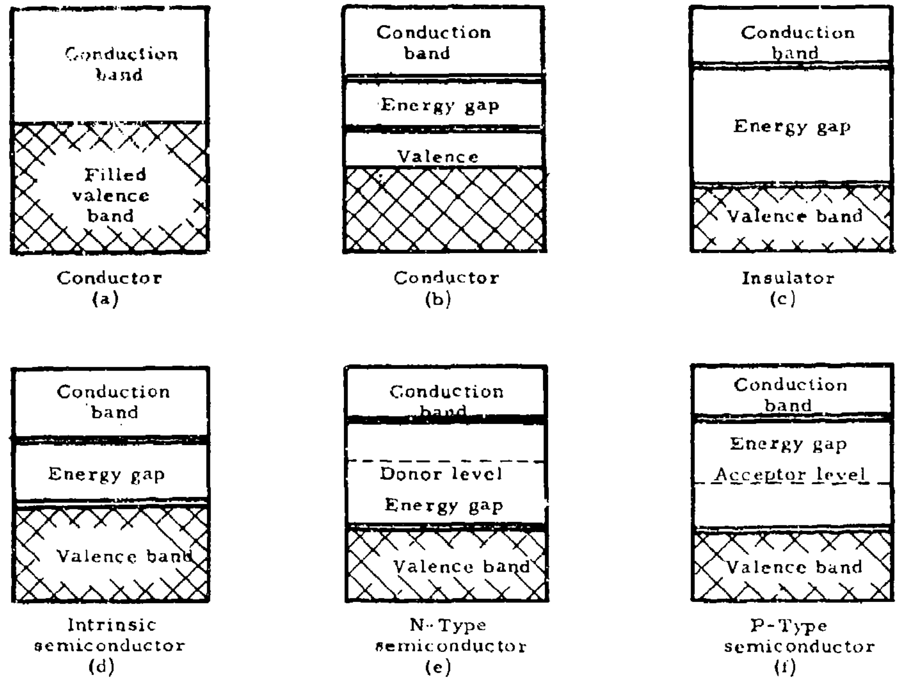


Fig. IV-12 Energy Band Configuration for Various Conduction Mechanisms

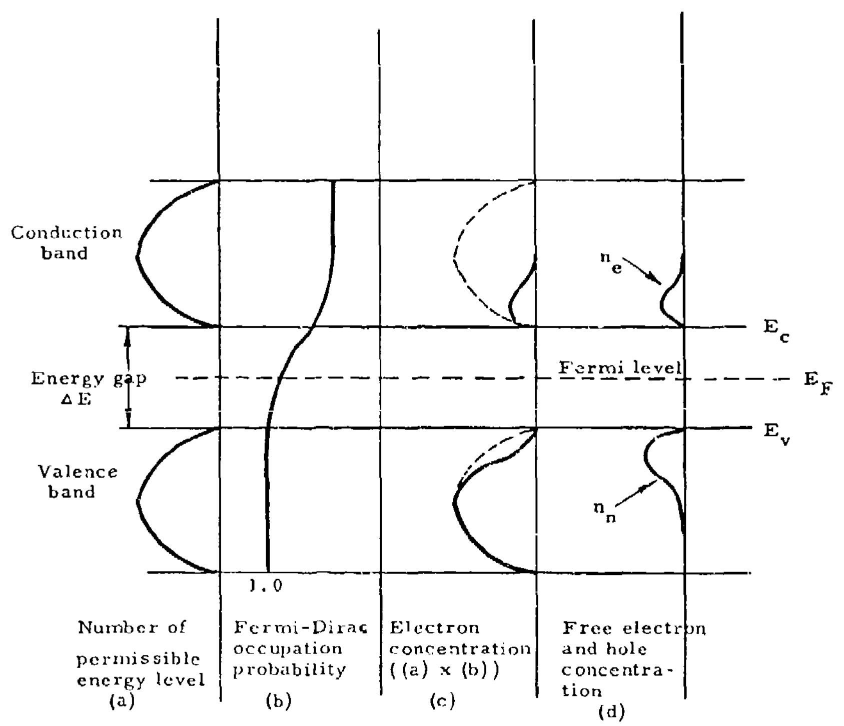


Fig. IV-13 Effect of Fermi-Dirac Statistics Upon Free Electron and Hole Concentrations in a Semi-conductor.

electrons per unit volume having energies from E to dE is given by

$$dn_e = \frac{4\pi(2m)^{3/2}\, E^{1/2}\, dE}{h^3 \; e^{(E - E_F)/kT} + 1} \qquad (2\text{-}10)$$

Each energy level has a definite velocity related to it be $E = 1/2\, mv^2$ where m equals mass and v equals velocity. It is therefore possible to develop the following expression for the number of electrons that arrive per unit time at a unit surface with energies in the range from E to dE.

$$dN = \frac{4\pi m\, kT}{h^3} \quad \ln \left[e^{(E_F - E)/kT} + 1 \right] dE \qquad (2\text{-}11)$$

To determine the number of electrons emitted from the surface of the conductor, it is now only necessary to integrate the above expression from E_a, the energy required to overcome the potential barrier, to infinity.

$$N = \frac{4\pi m\, kT}{h^3} \int_{E_a}^{\infty} \ln \left[e^{(E_F - E)/kT} + 1 \right] dE \qquad (2\text{-}12)$$

For all practical cases, E_F - E is in the range of 20kT, and E is always greater than E_F, therefore, $e^{(E_F - E)/kT}$ is much smaller than one. The equation can than be reduced to:

$$N = \frac{4\pi\, m\, kT}{h^3} \int_{E_a}^{\infty} e^{(E_F - E)/kT} \, dE \qquad (2\text{-}13)$$

$$N = \frac{4\pi\, m\, k^2\, T^2}{h^3}\, e^{-(E_a - E_F)/kT} \qquad (2\text{-}14)$$

Since each electron carries a charge Q, the emission current density J equals QN.

$$J = \frac{4\pi\, m\, Qk^2\, T^2}{h^3} \; e^{-(E_a - E_F)/kT} \qquad (2\text{-}15)$$

Setting $4\pi\, m\, Q\, k^2/h^3 = A$

and $E_a - E_F/k$ = work function/k = b

The above equation becomes Richardson's Equation:

$$J = A\, T^2\, e^{-b/T} \qquad (2\text{-}16)$$

c. Bridge Techniques in Temperature Measurements (Ref. IV-4)

The Half Bridge

Table I summarizes the bridge equations for the various configurations. The first type shown in (a) is termed the half bridge because two power supplies replace the single supply and the two arms of the full bridge shown in (c). The bridge output, measured across detection arm Rg, is:

$$E_g = \frac{E_1/R_1 - E_2/R_p}{1/R_g + 1/R_1 + 1/R_p} \qquad (1)$$

The transducer is represented by R_p.

The null condition, obtained when Eg is zero, occurs when the numerator of the right hand side of (1) is zero.

$$R_p = R_{po} = R_1 \frac{E_2}{E_1} \qquad (2)$$

The value of R_p, which is a function of temperature, that nulls the bridge is defined as R_{po}, and deviation from this value, ΔR.

Therefore:

$$R_p = R_{po} + \Delta R \qquad (3)$$

For materials usually employed in a resistance transducer, R_p varies linearly with temperature and, for limited ranges, may be adequately described by the linear approximation:

$$R_p = R_p(T_o)\,(1 + k\Delta T) \qquad (4)$$

The factor k in (4) is defined as the temperature coefficient of resistivity in ohms/ohm/degree and is usually given at 68°F (20°C). For purposes of this discussion, T_o is the temperature at which the bridge is nulled; $R_p(T_o) = R_{po}$ is the corresponding resistance of the transducer; and ΔT is the temperature change from T_o.

In equation form:

$$R_{po} = R_p(T_o)$$
$$\Delta R = R_{po} k \Delta T \qquad (5)$$
$$k = \frac{1}{\Delta T}\left(\frac{R_p(T_o + \Delta T)}{R_p(T_o)} - 1\right)$$

The equation relating output to resistance variation, obtained by substituting (2) and (3) in (1), is

$$E_g = \frac{\frac{E_1}{R_1}\Delta R}{1 + \frac{E_2}{E_1}\left(1 + \frac{R_1}{R_g}\right) + \frac{\Delta R}{R_1}\left(1 + \frac{R_1}{R_g}\right)} \qquad (6)$$

From (4) and (6), two sensitivities may be derived. The first relates output voltage, Eg, to resistance change about the null and has the dimensions of current:

$$E_g \sim S_1 \Delta R \Big|_{\Delta R = 0}$$

$$S_1 = \frac{E_1}{R_1}\,\frac{1}{1 + R_1\left(\frac{E_2}{E_1}\right)\left(\frac{1}{R_1} + \frac{1}{R_g}\right)} \qquad (7)$$

The second sensitivity relates the output voltage to changes in temperature:

$$E_g \sim S_2 \Delta T \Big|_{\Delta T = 0}$$
$$\sim S_1 R_1 k \left(\frac{E_2}{E_1}\right) \Delta T \qquad (8)$$
$$S_2 = E_2 k \,\frac{1}{1 + R_1 \frac{E_2}{E_1}\left(\frac{1}{R_1} + \frac{1}{R_g}\right)}$$

A special case of great interest occurs when $E_1 = E_2 = E$ and $R_1 = R_g = R$. Then:

$$E_g = \frac{E}{3R}\Delta R$$
$$= \frac{Ek}{3}\Delta T \qquad (9)$$

A practical condition often placed on a bridge is the self heating limitation within the transducer, expressed as the number of watts dissipated within the probe to yield one degree temperature rise for a particular set of ambient conditions. Generally, the most conservative value is for the unmounted transducer in still air. In all other cases, the temperature change for the same power level will be less; an example is a probe mounted on a plate or heat sink. The probe manufacturer generally provides W_m, the power sensitivity, or power which may be dissipated in the probe to achieve a given rise. This, in turn, provides a constraint upon E_2 for the split bridge as follows:

$$E_2 < \sqrt{R'_p W_m}\,. \qquad (10)$$

In (10), R'_p is the minimum expected value of R_p. When the bridge is operated from null with only a positive output, then:

$$R'_p = R_{po}$$

Under these circumstances, the output is related to the bridge constants by

$$E_g = \frac{\Delta R}{3}\sqrt{\frac{W_m}{R_{po}}}\,. \qquad (11)$$

Equation (11) defines the maximum sensitivity for the symmetrical half bridge in terms of the probe parameters alone. Similar constraints may be calculated for the general case of the half bridge and the full bridge.

The half bridge finds its best application when there are a large number of channels, since point a of Table Ia may be grounded and the output measured from b to ground, permitting the power supplies to be common to all channels, and reducing the cost per channel. However, two precautions must be considered when employing the half bridge. The first precaution: R_p must be large relative to any lead wire resistance to prevent errors due to the

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Ref. IV-4 "Bridge Techniques in Temperature Measurement," Astra Technical Instrument Corp., Sub., of Arnoux Corp., Application Bulletin No. 2.

variation of lead wire resistance with temperature. If this is not possible, then the Siemans three-wire equivalent bridge of Fig.14 b may be employed with the condition that $R_1 = R_p(T_o)$. Since the lead wire resistance contributes equally to both legs of the bridge, the balance point is undisturbed by lead wire resistance. However, sensitivity factors are decreased by the ratio of lead wire resistance to leg resistance, and sensitivity also becomes a function of the change in lead wire resistance due to ambient temperature variations. The null condition, however, is unaffected by temperature variations in the lead wires.

A second precaution in employing the half bridge: If, through any cause, the power supply outputs do not change in the same proportion, then a fraction of the difference of the absolute values of their voltages will appear as an output voltage. Thus, small power supply output changes can yield large errors, since E_1 and E_2 are large relative to the available output. For example, if E_1 and E_2 are 28 volts and R_g is large enough to be neglected, then an increase in E_1 to 30 volts would increase the output by half the change, or one volt. This would represent a large error relative to the typical full scale of 5 volts. To minimize this requires highly regulated bridge power supplies designed to be extremely stable or coupled so that they vary in the same proportion.

In practice, E_1 and E_2 are generally not lower than approximately 5 volts. This, in turn, limits the half bridge to probes in the 10,000 ohm class.

Fig 14 a illustrates a practical half bridge circuit with zero and span adjustments. In application, R_1 is adjusted for the desired output voltage at, for example, a specified upper temperature, and R_g, a potentiometer, is varied for any desired sensitivity below the maximum available. As shown, the adjustments are independent.

For convenience, a precision adjustable resistor is often substituted for the transducer, and the zero and span are established from the calibration chart supplied with the transducer by the manufacturer.

With $E_1 = E_2 = 28$ volts, $R_g = 20{,}000$ ohms, and $R_1 = R_{po} = 20{,}000$ for a Balco probe element for which $k = 0.0045\ \Omega/\Omega/°C$, the probe dissipation is approximately 39 milliwatts, yielding a small self-heating error. The output sensitivity is large enough for the bridge to yield an output change of 5 volts for a 300°F temperature change.

One further point: The nonlinearity of the bridge may be used to advantage with a probe element that has a positive second order resistance temperature coefficient, as in Balco, nickel, and tungsten. The bridge can be made to compensate for the nonlinearity of the resistance-temperature curve, yielding an output voltage which is relatively linear over a wide temperature span.

Transducer-bridge linearization may be accomplished by determining the best power series for the resistance-temperature curve in the range of interest and by matching it to the power series expansion of E_g. By matching the terms of the series, the bridge constants may be determined to minimize the nonlinearity.

The Thermistor Linearization Bridge

Thermistors, since they are related to temperature by an exponential function, are not linear in any sense. However, they are highly sensitive to temperature changes and find wide use in resistance thermometry. One method of extending the equivalent linear range of a thermistor is by employing the circuit shown in Table 1b. The combination of the thermistor with the voltage divide circuit yields

$$E_g = \frac{ER_T}{R_1 + R_T} = \frac{EAe^{B/T}}{R_1 + Ae^{B/T}} \qquad (12)$$

$$R_T = Ae^{B/T}$$

By choosing R_1 with the value:

$$R_1 = \frac{B - 2T_o}{B + 2T_o} R_T(T_o), \qquad (13)$$

the second order term of the expansion of Equation (12) is zero and the maximum error in degrees is

$$\epsilon \max \leqq 0.03\ \Delta T^4\ B^2/T_o^4 \qquad (14)$$

over the span ΔT.

It is important to note that T must be in degrees Kelvin or Rankine if the scale is in Centigrade or Fahrenheit, respectively. The method can be readily extended to bridge applications if the detection arm presents a small load to the bridge arms.

Thermistor circuits have been constructed in this manner linear to within .2°F over the range 36 to 90°F.

The Full Bridge

General Case

The resistance bridge of Table 1c may be employed either in the nulling sense to measure probe resistance or as a means for converting variations in temperature to voltage across detection arm R_g. The exact equation relating bridge output to resistance is

$$E_g = \frac{E\ R_g\ (R_1R_p - R_2R_4)}{R_2(R_1+R_4)(R_g+R_p+R_4) + R_1P_pR_4 - R_2R_4^2 + R_gR_p(R_1+R_4)} \qquad (15)$$

If R_p is approximated by (4), then the null condition obtained, as with the split bridge, is

$$R_{po} = R_2R_4/R_1. \qquad (16)$$

The equation for the deviation about null is:

$$E_g = \frac{E\ R_g \left(\frac{R_1}{R_1 + R_4}\right) \Delta R}{R_2 \left[R_g + R_4 + \frac{R_4}{R_1}(R_2 + R_g)\right] + \Delta R \left[R_2 + R_g + \frac{R_1R_4}{R_1 + R_4}\right]} \qquad (17)$$

Assuming the same sensitivity definitions as with the split bridge, then:

$$S_1 = \frac{ER_g \left(\frac{R_1}{R_1 + R_4}\right)}{R_2 \left[R_g + R_4 + \frac{R_4}{R_1}(R_2 + R_g)\right]} \qquad (18)$$

$$S_2 = \frac{kER_g \left(\frac{R_4}{R_1 + R_4}\right)}{R_g + R_4 + \frac{R_4}{R_1}(R_2 + R_g).} \qquad (19)$$

Resistance in series with the supply, E_1, does not affect the null. However, the source appears more like a current source than a purely voltage source and this does affect bridge sensitivity. Replacing the voltage source with a current source also has the effect of linearizing the bridge output for a given R_g, which often is highly desirable. This point will be discussed in a later section.

The Half Symmetrical Bridge

A number of special cases of the full bridge are particularly interesting. The first of these is when

$$R_1 = R_2 = R$$
$$R_4 = R_{po} = mR.$$

In this case the two resistors in the upper half are equal, requiring the two in the lower half to be equal at null. Then

$$E_g = \frac{E(R_g/R)\ \Delta R}{R(m+1)\left[2m+\frac{R_g}{R}(m+1)\right]+\Delta R\left[2m+1+\frac{R_g}{R}(m+1)\right]} \tag{20}$$

$$S_1 = \frac{E\ (R_g/R)}{(1+m)\ \left[2mR+R_g\ (m+1)\right]} \tag{21}$$

$$S_2 = \frac{E\ mR_g\ k}{(1+m)\ \left[2mR+R_g(m+1)\right]}. \tag{22}$$

These equations apply to the three bridge configurations of Fig 15 in which the transducer resistance at bridge null is equal to mR. This causes the effect of lead wires and variations in the lead wire resistance to act equally in both legs of the bridge so that the null is undisturbed. For the same configuration, variations in R_1 appear in series with the power supply and also alter the effective value of m, changing the sensitivity constants of the bridge.

It is important to know the relationship between R_g, R and m for maximum power transfer to R_g. This is desirable for those cases where a power amplifier (such as a magnetic amplifier), as opposed to a voltage amplifier (vacuum tube), is employed as the load or bridge detection arm. For maximum power transfer, R_g is related to m and R by

$$R_g = R\frac{2m}{1+m}, \tag{23}$$

$$\text{and } E_g = \left(\frac{2m}{m+1}\right)\frac{E\Delta R}{(m+1)\ \ 4mR+\Delta R\ (4m+1)} \tag{24}$$

$$E_g \sim \frac{E\Delta R}{2R\ (1+m)^2} = \frac{Em\ k\ \Delta T}{2\ (1+m)^2}. \tag{25}$$

The Completely Symmetrical Bridge

In the case of the completely symmetrical bridge, for which $m = 1$,

$$E_g = \frac{E\ \frac{R_g}{R}\ \Delta R}{4\ (R_g+R)+\frac{\Delta R}{R}\ (2R_g+3R)} \tag{26}$$

$$S_1 = \frac{E}{4R_g}\left(\frac{R}{R+R_g}\right) \tag{27}$$

$$S_2 = \frac{E}{4}\left(\frac{R_g}{R+R_g}\right)k. \tag{28}$$

For maximum power transfer in this case, $m = 1$, $R_g = R$, and

$$E_g = \frac{E\Delta R}{8R+5\Delta R}\sim\frac{E}{8R}\ \Delta R = \frac{E}{8}\ k\Delta T \tag{29}$$

To determine the value of m (the degree of dissymmetry in a half symmetrical bridge) under, for example, maximum power transfer conditions, Equation (23) may be substituted in (20), and the result rewritten as:

$$\frac{E_g}{E} = a\ \frac{X}{1+bX}$$

where

$$a = \frac{m}{2(m+1)^2}$$
$$b = \frac{4m+1}{4(m+1)}$$
$$X = \frac{\Delta R}{mR}$$

This equation is plotted for various values of m as a function of X.

Note that as m decreases the effective sensitivity at null also decreases, but not in the same proportion, and that the curves become more linear. In the temperature transducer application, since the power dissipated in the probe is specified at some maximum value, then E_{bm}, the maximum value of the bridge power supply voltage, is permitted to increase by the factor (m + 1), raising the effective sensitivity. The table included in Fig 16 illustrates that the sensitivity under these conditions actually is higher than in the symmetrical case, where m = 1 all referred to the latter, as in column 4 of the table. Further, the curve of bridge output versus X is considerably more linear than in the symmetrical case.

The expenses of achieving these two benefits are a higher power supply voltage and an increased power dissipation in the bridge. However, both are nominal. There is relatively little advantage in making m smaller than 0.1 to 0.2.

Power Limitations

As in the case of the split bridge, the full bridge voltage is determined by the power sensitivity of the resistance transducer for a given application. The voltage across the probe at null is given by Equation (10) and it follows for the case of the half symmetrical bridge that:

$$E_{max} = E_p \frac{(m+1)}{m} = \frac{(1+m)}{m} \sqrt{WmmR} \qquad (30)$$

For the symmetrical bridge:

$$E_{max} = 2\sqrt{WmR} \qquad (31)$$

To secure still larger voltages, the bridge may be pulsed. In this way, the bridge output, a square wave, may be quite large if the duty cycle is small, limited now only by the average power dissipation and the peak voltage specified for the probe element and housing. This technique is particularly useful when a number of temperatures are to be measured and a commutated output signal is desired. It is important to note that if the bridge output is to be single ended and one side of the detection arm common, then one power source must be provided for each bridge. If the output is differential then a common supply may be provided for a number of bridges for economy.

Reduction of Lead Wire Effects

Fig.15a illustrates a bridge with independent and variable null and span adjustments. As discussed previously, the null is a function of lead wire resistance and of variations in the resistance. The three-wire bridge was conceived by W. Siemens in 1871 as a means for eliminating the effect of lead wire resistance in the null. Several examples of three wire bridges are shown in (b) and (c). A rheostat is generally placed in series with the transducer to null the bridge. However, variation in the contact resistance of the rheostat upsets the bridge null which limits the bridge usefulness to relatively high resistance transducers. Fig. 15d illustrates a variation of the bridge with four-wire compensation.

For the case in Fig. 15d:

$$E_g \sim \frac{E R_g \Delta R}{4mR\left[R_g + \left(\frac{m+1}{2}\right) R\right]} \qquad (32)$$

$$\sim \frac{E R_g k \Delta T}{4\left[R_g + \left(\frac{m+1}{2}\right) R\right]} \qquad (33)$$

For maximum power transfer:

$$R_g = (1+m)\frac{R}{2} \qquad (34)$$

and

$$E_0 \sim \frac{E\Delta R}{8mR} \qquad (35)$$

$$\sim \frac{E}{8} k \Delta T \qquad (36)$$

As for the three-wire case, variations in lead wire resistance are distributed equally in both arms and thus do not affect the bridge null but do change m.

By adding a potentiometer as in Fig 15e the bridge becomes the Callendar-Griffiths Bridge which provides complete null compensation if $R_1 = R_4$. This type of bridge has an advantage over the three-wire types in that the contact resistance of the null potentiometer is placed in series with R_g and for all practical purposes may be neglected. By eliminating the effect of lead wires and contact resistance, the Callendar-Griffiths Bridge is particularly useful when the transducer resistance is low — in the order of 10 to 100 ohms.

In the three-wire bridge of Figs15b and 15c some linearization is secured by making m small, as noted previously; useful results are obtained for m ranging as low at 0.1 to 0.2.

It is important to note that variations in the power supply voltage do not affect bridge null but do alter the sensitivity factor in direct proportion.

Example

An example of the use of the full bridge is now of interest. Assume a temperature probe of 1000 ohms with a maximum power dissipation of 10 mw for a 1°F self-heating error. It is desired to secure maximum power to the bridge detection arm in a completely symmetrical bridge. For this case, from Eq. (10):

$$E_m = \sqrt{W_m R} = \sqrt{0.01 \times 1000} = 3.16.$$

The value $E_m = 3.16$ limits the self-heating error to 1°F. For maximum power transfer, m = 1, and the voltage across the bridge is:

$$E = 2 \times 3.16 = 6.32 \text{ volts.}$$

Since $m = 1$, $R_1 = R_2 = R_4 = 1000$ ohms.

The null condition is $R_p = 1000$ ohms and

$$E_g \sim \frac{E}{8R} \Delta R = .79 \times 10^{-3} \Delta R.$$

This is a sensitvity factor of approximately .8 mv/ohm. Assuming a probe wound with Balco wire for which $k = 0.0025\ \Omega/\Omega/°F$,

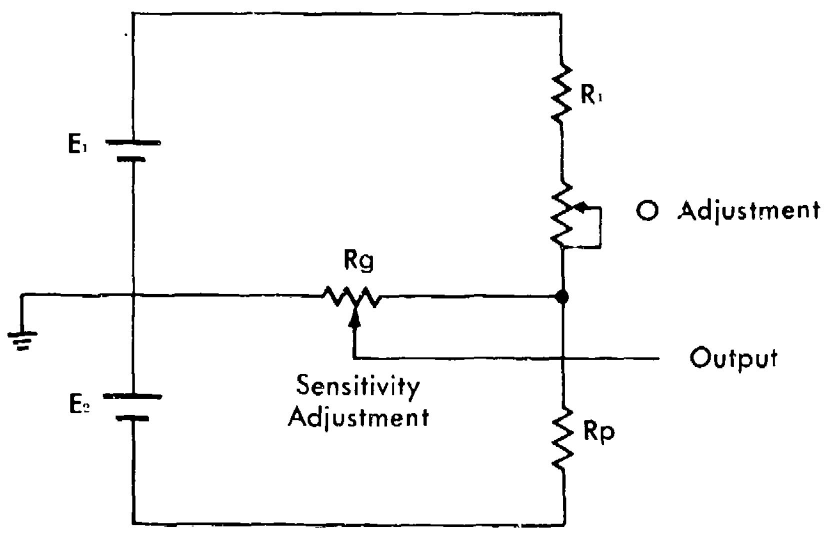
$$E_g \sim \frac{E}{8} k \Delta T = 1.98 \times 10^{-3} \Delta T$$

for a sensitivity of approximately 1.98 mv per °F. The resistance of the detection arm must be

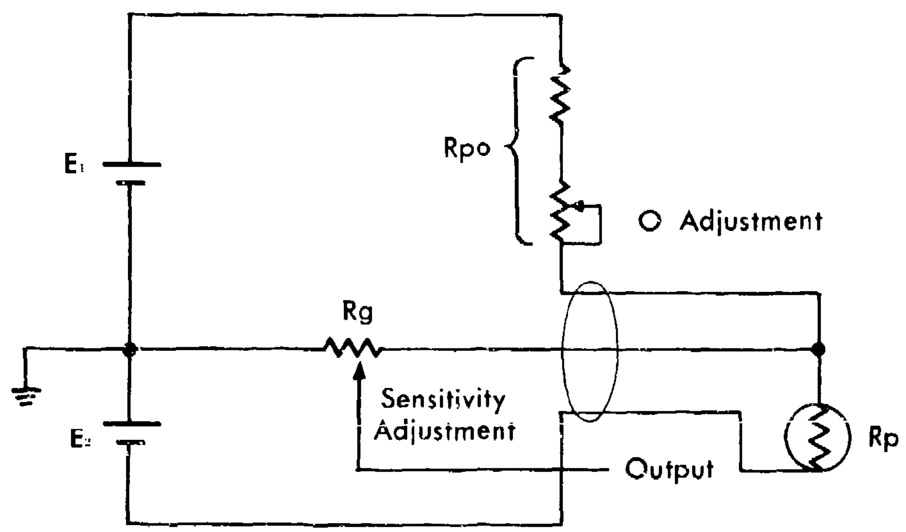
$$R_g = R = 1000 \text{ ohms}$$

and the power available for a 1.8°F (1°C) deviation from null is

$$W = E^2/R = \frac{(3.5 \times 10^{-3})^2}{1000} = 0.012 \text{ microwatts}$$



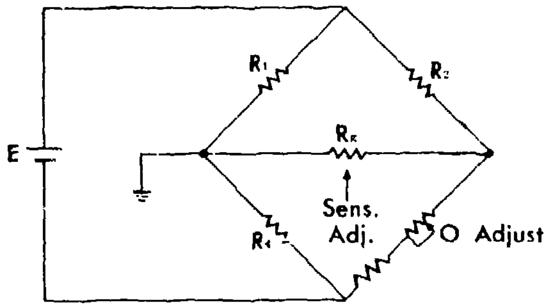
a. A Practical Split Bridge



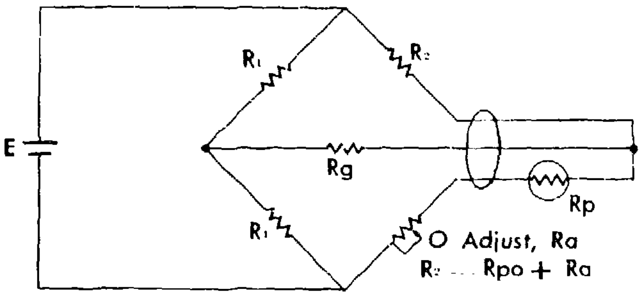
b. A Practical Split Bridge with Lead Wire Compensation

Fig. IV-14 Practical Split Bridge Circuits

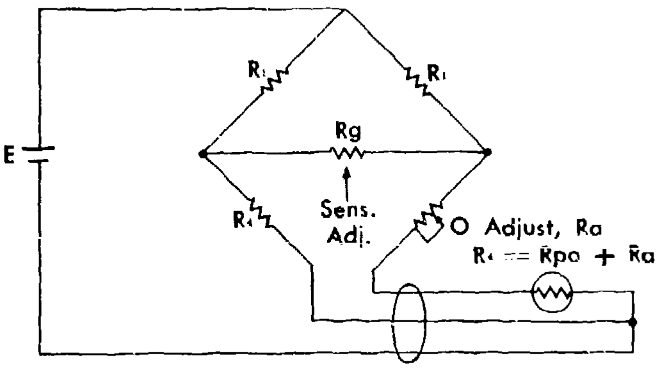
Fig. IV-15 Examples of Full Bridges



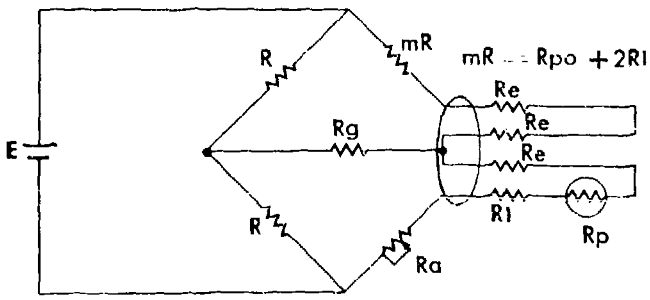
a. A Full Bridge With Zero and Sensitivity Adjustments



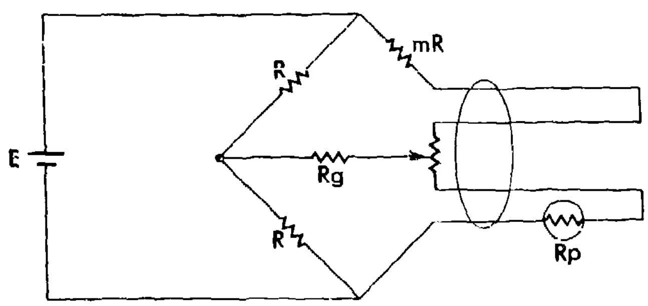
b. Siemans 3 Wire Bridge



c. A Variation on the Siemans 3 Wire Bridge



d. A Four Wire Bridge



e. Callendar Griffiths Bridge Adapted for a Four Wire Lead

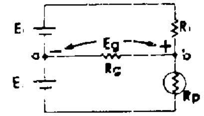
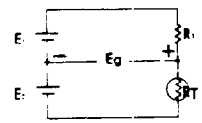
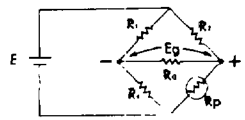
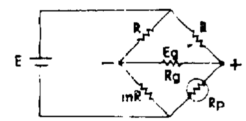
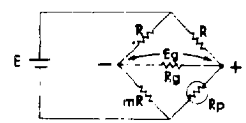
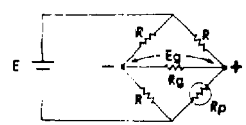
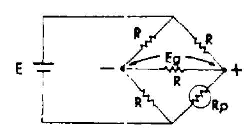
TYPE	CONFIGURATION	CONDITIONS	NULL	SENSITIVITY	EXACT EQUATION	COMMENTS
a. Half Bridge			$R_p = \frac{R_1 E_2}{E_1}$	$S_1 = \frac{E_1}{R_1} \frac{1}{1 + R_1 \frac{E_2}{E_1}\left(\frac{1}{R_1} + \frac{1}{R_g}\right)}$ $S_2 = kE_1 \frac{1}{1 + R_1 \frac{E_2}{E_1}\left(\frac{1}{R_1} + \frac{1}{R_g}\right)}$		
b. Thermistor Bridge-Linearized		$R_T = Ae^{B/T}$ $R_1 = \frac{B-2T_o}{B+2T_o} R_T(T_o)$	$R_T = R_1(T_o)$ $E_1 = E\left(\frac{1}{2} - \frac{T_o}{B}\right)$ $E_2 = E\left(\frac{1}{2} + \frac{T_o}{B}\right)$		$E_g = \frac{E}{1 + \frac{B-2T_o}{B+2T_o} e^{\dots}}$	$\epsilon_{max} < \frac{0.03(T-T_o)^3 B^2}{T_1}$
c. Full Bridge		$R_p = R_{po} + \Delta R$	$R_{po} = \frac{R_1 R_2}{R_3}$	$S_1 = \frac{E R_g \left(\frac{R}{R_1 + R_2}\right)}{R_1\left[R_g + R_1 + \frac{R_2}{R_1}(R_1 + R_g)\right]}$ $S_2 = \frac{E R_g \left(\frac{R_1}{R_1 + R_2}\right) k}{\left[R_g + R_1 + \frac{R_2}{R_1}(R_1 + R_g)\right]}$	$E_g = \frac{E R_g \left(\frac{R_1}{R_1 + R_2}\right) \Delta R}{R_1\left[R_g + R_1 + \frac{R_2}{R_1}(R_1 + R_g)\right] + \Delta R\left[R_1 + R_g + \frac{R_1 R_2}{R_1 + R_2}\right]}$	
d. Half Symmetrical Bridge		$R_1 = R_2 = R$ $R_3 = mR$ $R_{po} = mR$	$R_{po} = mR$	$S_1 = \frac{E R_g}{R(1+m)[(1+m)R_g + 2mR]}$ $S_2 = \frac{E m R_g k}{(1+m)[(1+m)R_g + 2mR]}$	$E_g = \frac{E \frac{R_g}{R} \Delta R}{R(m+1)\left[2m + \frac{R_g}{R}(m+1)\right] + \Delta R\left[2m + 1 + \frac{R_g}{R}(m+1)\right]}$	
e. Half Symmetrical Bridge — Maximum Power Transfer to Rg		$R_1 = R_2 = R$ $R_g = R\frac{2m}{1+m}$ $R_{po} = R_3 = mR$	$R_{po} = mR$	$S_1 = \frac{E}{2R(1+m)^2}$ $S_2 = \frac{E m k}{2(1+m)^2}$	$E_g = \frac{2m}{m+1} \frac{E \Delta R}{(m+1)4mR + \Delta R(4m+1)}$	
f. Completely Symmetrical Bridge		$R_1 = R_2 = R_3 = R_g$ $R_{po} = R$	$R_{po} = R$	$S_1 = \frac{E}{4R} \frac{R_g}{R + R_g}$ $S_2 = \frac{Ek}{4} \frac{R_g}{R + R_g}$	$E_g = \frac{E R_g \Delta R}{4R(R_g + R) + \Delta R(2R_g + 3R)}$	
g. Completely Symmetrical Bridge with Maximum Power Transfer to Rg		$R_1 = R_2 = R_3 = R_g = R_{po} = R$	$R_{po} = R$	$S_1 = \frac{E}{8R}$ $S_2 = \frac{Ek}{8}$	$E_g = \frac{E \Delta R}{8R + 5\Delta R}$	

Table IV-1 Summary of Bridge Equations

3. THRUST MEASUREMENT FUNDAMENTALS (Ref. IV-5)

a. Accelerometer Technique

Basically, the output of three accelerometers, mounted such that each corresponds to the acceleration components along each of three platform oriented axes, is combined with outputs from force sensors and a mass flow meter to solve for both the magnitude and direction of the vehicle thrust. No special device for measuring the gravitational acceleration is required since the accelerometer outputs correspond to the algebraic sum of the inertial acceleration $\ddot{\vec{r}}$ and the gravitational acceleration $\vec{g}_L$. Hence, calling the output acceleration from each accelerometer a_i the total acceleration vector as determined by a system of three mutually orthogonal accelerometers mounted on a thrusting vehicle will be

$$\begin{aligned} \vec{a} &= \ddot{\vec{r}} - \vec{g}_L \\ &= a_1 \vec{1}_1 + a_2 \vec{1}_2 + a_3 \vec{1}_3 \end{aligned} \tag{3-1}$$

where 1_1, 1_2, and 1_3 represent the unit vectors in the direction of each of the three accelerometer axes, respectively. The function of a computer to solve for the rocket thrust is then reduced to that of mechanizing a solution to the now modified thrust equation

$$\vec{T} = M \vec{a} \sum_{i=1}^{i=n} \vec{F}_i \tag{3-2}$$

The two most significant external forces that a vehicle will encounter over its flight path will be the aerodynamic drag and lift forces. When a high velocity condition prevails, the aerodynamic drag force is quite large. If the rocket engine is canted or swivelled so that it is not thrusting along the longitudinal axis of the vehicle, a component of the lift force exists in the direction of thrust and must be accounted for. A direct measure of these forces seems unlikely; therefore, a means must be provided for estimating these forces based on measurable quantities. The drag force, for example, which depends on the air density, velocity of the vehicle, angle of attack, and effective drag geometry might to a first approximation, be estimated by measuring the velocity of the vehicle and the air density directly, or relating the density to a measure of the altitude. Similar approaches would apply equally as well to the determination of the lift force or any other significant aerodynamic forces. Admittedly, these

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Ref. IV-5 Same as Ref. 227B.

estimates might be crude, but in a high thrust condition such an approach might be adequate. Refinements in the estimate could be made, but at the expense of additional complexity.

For flight regimes outside the atmospheric envieonments of any planet, the aerodynamic forces become negligible and the determination of the vehicle thrust vector involves simply a solution to the equation.

$$\vec{T} = M\,(a_1\,\vec{1}_1 + a_2\,\vec{1}_2 + a_3\,\vec{1}_3) \sum_{i=1}^{i=n} \vec{F}_1 = 0 \qquad (3\text{-}3)$$

However, a complete accelerometer system for determining the in-flight thrust of a vehicle will, in general, include the capability of determining all forces acting on the vehicle. A functional diagram of the complete system is illustrated in Figure IV-16.

b. Application of Combined Accelerometer-Force Transducer to the V-2 Rocket System

An application of the accelerometer-force transducer technique is illustrated here using the characteristics of the German V-2 rocket. For this vehicle the weight W_1 (proportional to the mass M_1 in the text) is considered to be the entire propulsion unit which includes thrust chamber, generator, air bottle and thrust frame. This weight is approximately 2,000 pounds. W_2 at launch is 26,000 pounds and includes payload, fuel, and containing structure. In terms of mass then

$$\text{Mass 1 or } M_1 = \frac{2000}{g} \text{ slugs} \qquad (3\text{-}4)$$

and

$$M_2\,(t_o) = \frac{26000}{g} \text{ slugs} \qquad (3\text{-}5)$$

However, M_2 (t) is a variable with time and to calculate M_2 at any time during burning the following relationship is used:

$$M_2\,(t) = M_2\,(t_o) - \dot{m}t \qquad (3\text{-}6)$$

where $\dot{m}$ is the mass flow rate, assumed constant and t is the time. In the case of the V-2,

$$\dot{m} = \frac{300}{g} \text{ slugs/sec} \qquad (3\text{-}7)$$

and the total burning time is on the order of 65 seconds.

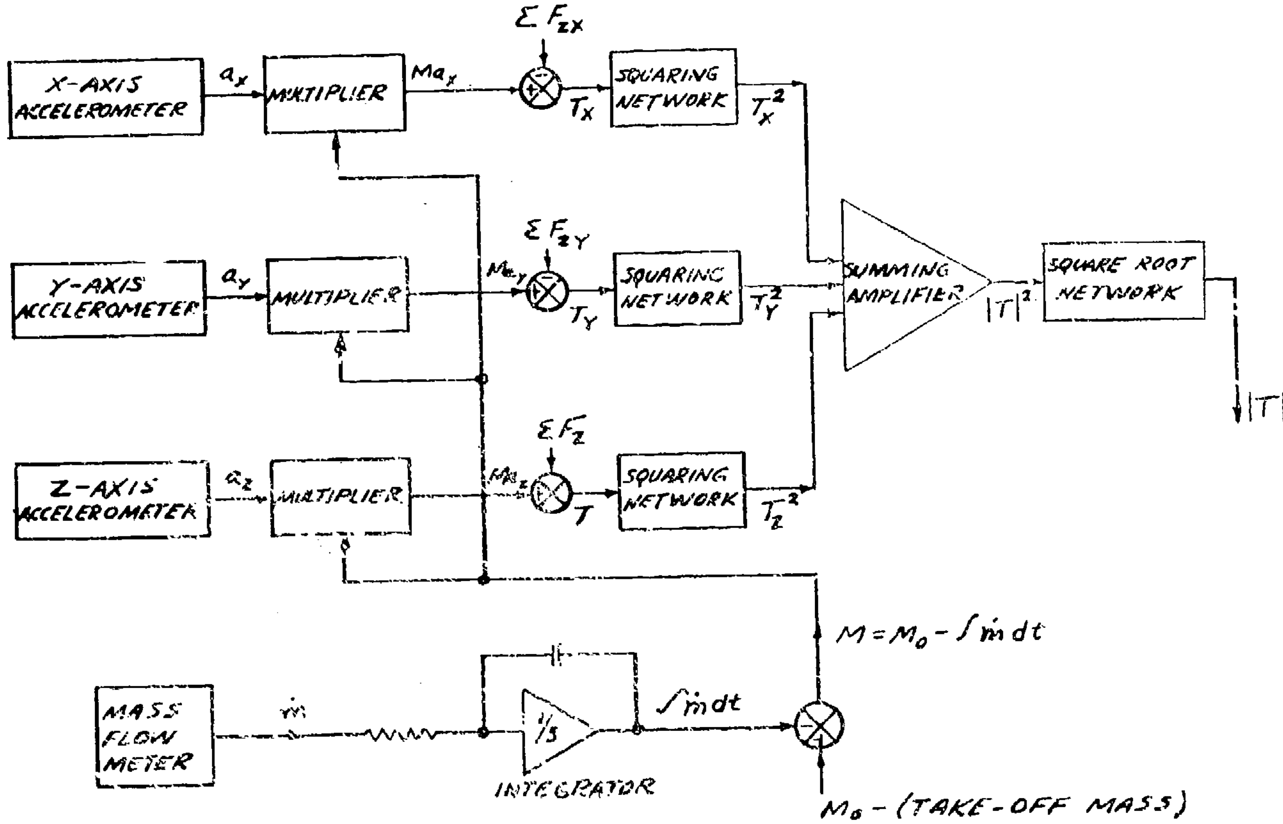


Fig. IV-16 Mechanization of the Thrust Equation

Figure IV-17 shows the acceleration which is applied to the vehicle during the time that thrust is applied. This is the acceleration which will be measured by an accelerometer in the vehicle.

Figure IV-18 shows the linear decrease in weight or W_2 due to expulsion of the fuel and is obtained from the previous equations.

These curves are applied to the equation previously developed for thrust:

$$T = M_1 a + P \qquad (3\text{-}8)$$

to develop Figure IV-19

The compression force P as measured by the force transducer between the mounting brackets and the forward mass M_2 (t) is presented in Figure IV-19 where P is given by

$$P = M_2 (t) a \qquad (3\text{-}9)$$

The relative magnitudes of the components which make u p the total thrust are apparent. Since the $M_1 a$ term is a small portion of the total, errors in M_2 due to different amounts of fuel being present in the motor or errors in the acceleration due to small structural deflections are relatively insignificant compared to the total value of thrust. There is one further point concerning variation in weight of fuel that is in the motor at any given time. That is the fuel makes up only 1/100 of the total motor weight, making its effect on errors in total thrust even more insignificant.

This technique can be applied to solid or nuclear rockets as well as liquids; however, special design considerations are necessary to make workable systems.

c. Liquid Propellant Systems

Consideration is made of the structural layout for a typical liquid propellant rocket, Figure IV-20, and a simplified one-dimensional example of the thrust phenomena in space, Figure IV-21 is presented. Writing the equations of motion we have

$$T = \left[M_1 + M_2 (t) \right] a \qquad (3\text{-}10)$$

where a is the total thrust acceleration of the entire mass system as measured by a system of accelerometers mounted on the vehicle.

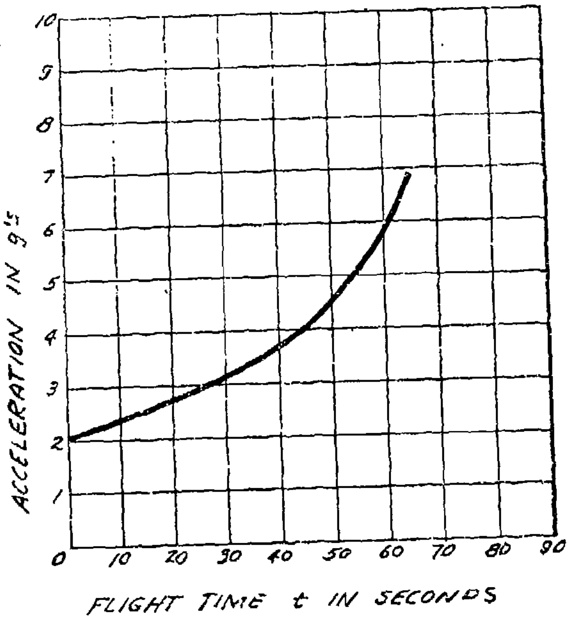


Fig. IV-17 Plot for Acceleration Versus Time of V-2 Rocket

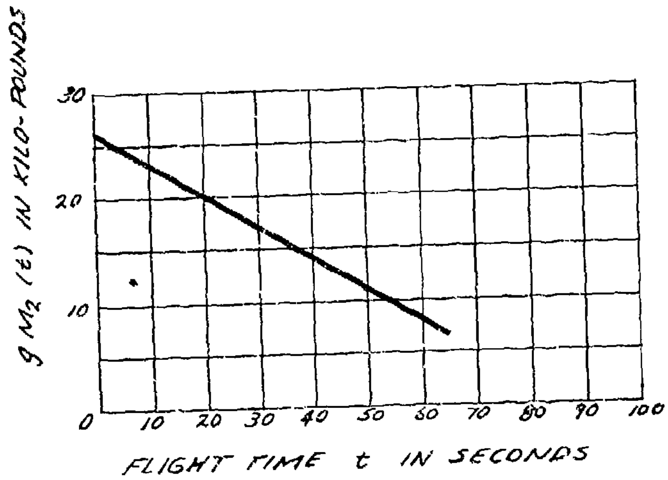


Fig. IV-18 Plot of gM2(t) For V-2 Rocket

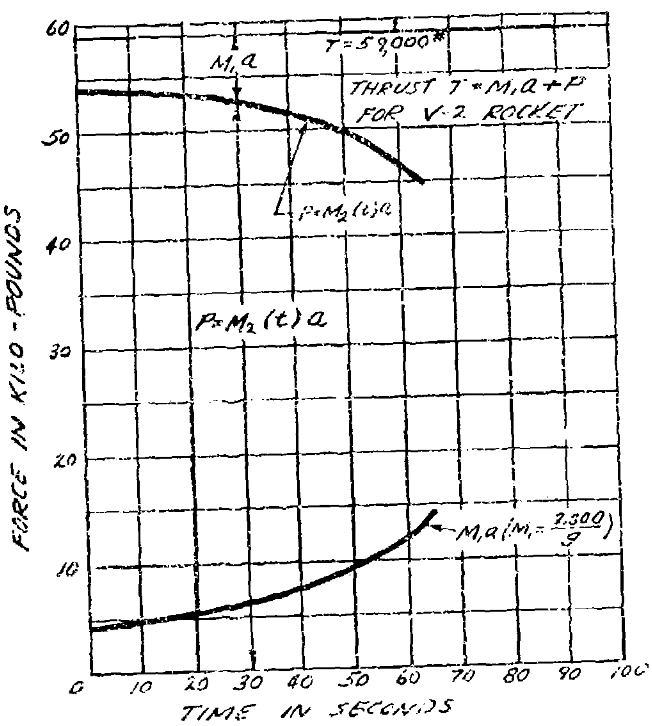


Fig. IV-19 Plot Showing the Variation in the Acceleration Forces with Time of Burning

The load P in the mounting bracket will be a compression given by the expression

$$P = T - M_1 a = M_2 (t) a \tag{3-11}$$

solving for T in Eq (3-10) yields

$$T = M_1 a + P \tag{3-12}$$

Now consider the vehicle in atmosphere. The two major external forces acting on a missile are gravity and aerodynamic influences. However, since seismic mass-spring type devices cannot distinguish between inertial and gravitational type acceleration, and both masses in this scheme are influenced by gravity, both sensors (to measure P and a) will measure force and accelerations relative to a freely falling body and the external force of gravity will not be sensed. The aerodynamic forces will influence the acceleration and load measurement as can be seen in the following development.

From Figure IV-22 we write the equation of motion for the entire mass system

$$T - D = \left[M_1 + M_2 (t) \right] a \tag{3-13}$$

and writing a free-body force relationship for M_2 (t) we obtain for the load P

$$P = D + M_2 (t) a \tag{3-14}$$

where D is the total drag force acting on the missile and is assumed to act only on the mass M_2 (t).

Solving for the thrust by substituting Eq (3-14) into Eq (3-13) we obtain

$$T = M_1 a + P \tag{3-15}$$

It can be noted that Eq (3-12) and (3-15) are identical showing that the only measurements necessary to determine thrust while in and out of the atmosphere are the acceleration and the force.

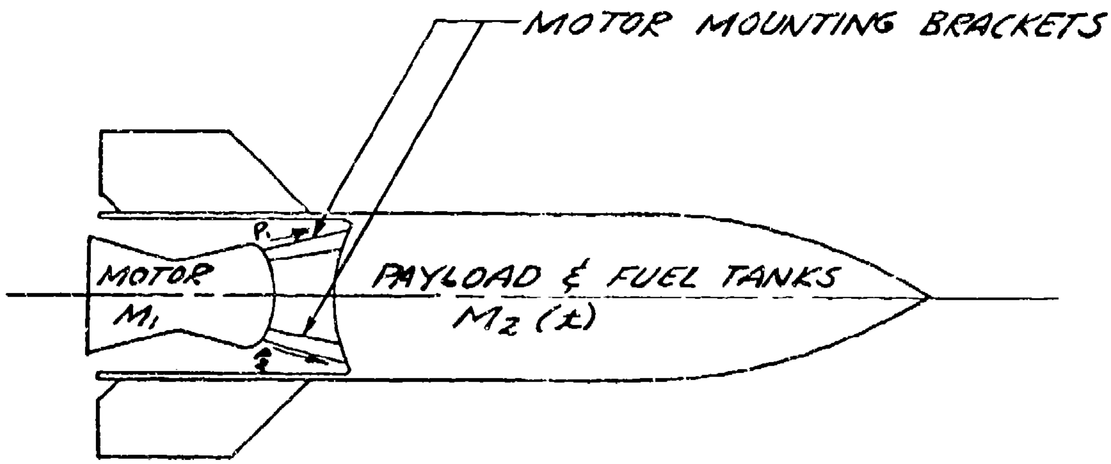


Fig. IV-20

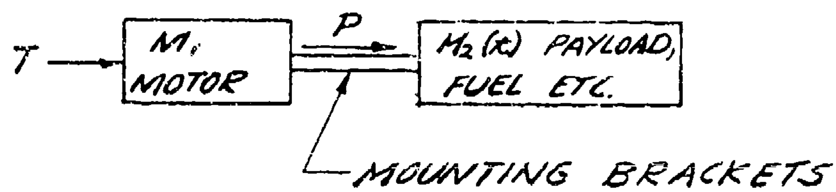


Fig. IV-21

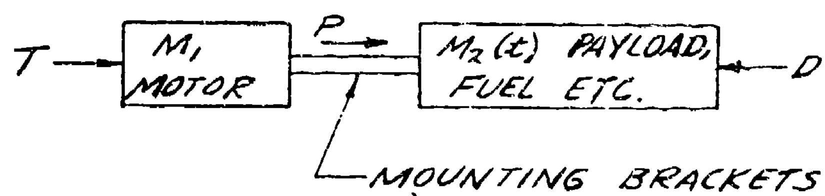


Fig. IV -22

Liquid Propellant Systems Diagrams

d. Solid Propellant Systems

An analysis of the combined accelerometer-force technique as applied to solid propellant rocket engines is illustrated by Fig. IV-23. In this diagram, $m_1(t)$ is the mass of the rocket motor and fuel, m_2 is the mass of the balance of the vehicle including structure, payload, etc. D is the drag force, T is the thrust of the motor, and P is the force measured by the transducer.

Summing the forces on the vehicle

$$\sum F = m_t a \tag{3-16}$$

$$T - D = \left[m_2 + m_1 \; (t) \right] a$$

Considering the payload portion of the vehicle only, the following equations can be written

$$\sum F = m_2 a$$

$$P - D = m_2 a \tag{3-17}$$

Combining Eq (3-16) and (3-17) produces

$$T = P + m_1 \; (t) \; a \tag{3-18}$$

but m_1 is a time varying function dependent on the rate of discharge of the propellant, which introduces the original accelerometer problem, the measurement of instantaneous weight.

However, this technique can be applied as well in solid propellant rockets as in liquid rocket motor with the approach shown in Figure IV-24. In this case, the force transducer is placed on the motor shell directly in front of the nozzle. The weight of the vehicle is broken down into M_1 wh ch is the mass of the nozzle and any gas which may be in it and $m_2(t)$ which includes the balance of the vehicle, i.e., payload, propellant, rocket motor case, etc. It is worth noting that m_1 is small relative to the balance of the vehicle.

In order to analyze this system, it is necessary to examine the method whereby thrust is produced in a rocket motor. The total force on a rocket motor can be considered as the sum of the pressure acting over the entire area or $\int P dA$. This is shown in Figure IV-25.

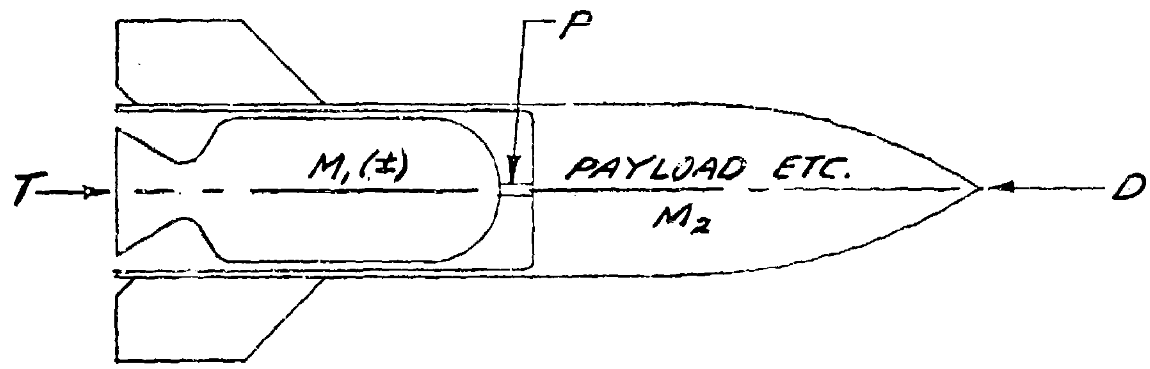


Fig. IV-23

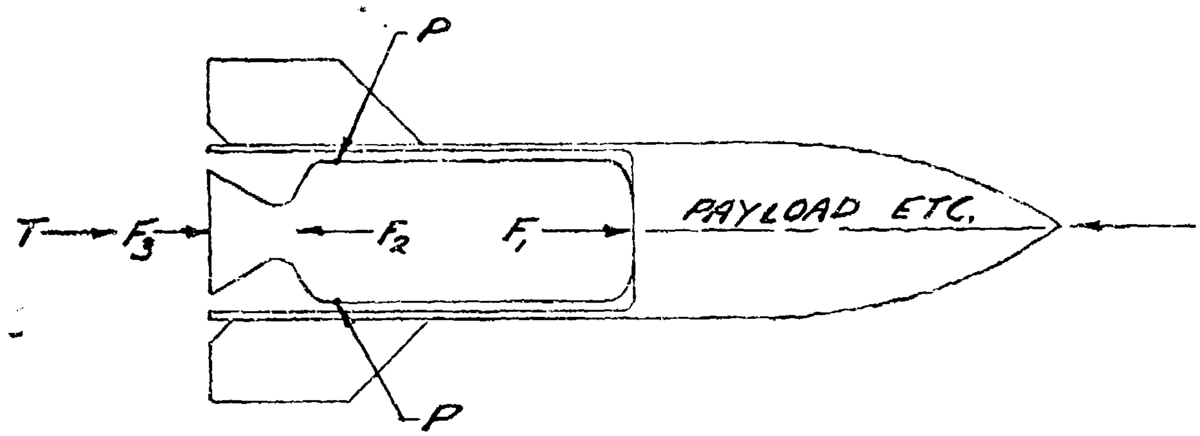


Fig. IV-24

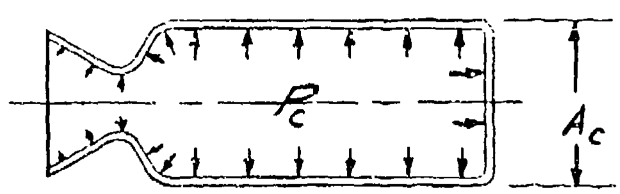


Fig. IV-25

Solid Propellant Systems Diagrams

Neglecting the pressure forces which do not act axially and, consequently, do not produce thrust, the remaining forces are:

1. The force caused by the pressure acting on the bulkhead
2. The force caused by the pressure acting on the convergent section of the nozzle.
3. The force caused by the pressure acting on the divergent section of the nozzle.

The force on the bulkhead is simply the chamber pressure times the cross sectional area or $F_1 = P_c A_c$. The pressure on the convergent section of the nozzle varies from chamber pressure down to throat pressure (approximately one-half chamber). The force produced by this pressure is equal to the integral of the pressure over the area of the convergent section of $F_2 = \int P_{con} dA_{con}$. The pressure on the divergent section of the nozzle varies from throat pressure down to something less than atmospheric. The force produced by this pressure is equal to the integral of the pressure over the area of the divergent section or $F_3 = \int P_{div} dA_{div}$. Summing up these forces and noting direction

$$\begin{aligned} T &= F_1 - F_2 + F_3 \\ &= P_c A_c - \int P_{con} dA_{con} + \int P_{div} dA_{div} \end{aligned} \tag{3-19}$$

With this in mind, assume the force measuring device is mounted immediately ahead of the nozzle and measures $F_3 - F_2$. This force is called P. Now the equation of motion for the vehicle can be written as follows:

$$T - D = \left[m_1 + m_2 (t) \right] a \tag{3-20}$$

recalling that m_1 is the mass of the nozzle and $m_2(t)$ the balance of the vehicle. Then considering the forces on m_2 (t) only, the following equation can be written:

$$F_1 - P - D = m_2 (t) a \tag{3-21}$$

Substituting this into the previous equation the desired result is obtained

$$\begin{aligned} T - \cancel{D} &= m_1 a + F_1 - P - \cancel{D} \\ T &= F_1 - P + m_1 a \end{aligned} \tag{3-22}$$

or, in another form

$$T = P_c A_c - P + m_1 a \qquad (3-23)$$

It is apparent that the only additional measurement necessary to convert this thrust measuring scheme to solid rockets in chamber pressure at the bulkhead of the motor. This value times the known cross-sectional area produces the additional term necessary in the thrust equation.

Here again, m_1 is small compared to the total, and any error due to unforeseen nozzle erosion will contribute insignificantly to the total error in the thrust measurement. The remaining terms in the equation are either known or accurate measurement is possible making accurate determination of thrust a reality.

e. Flight Thrustmeter, Theory of Operation (Ref. IV-6)

The net thrust of a turbo-jet engine is equal to the change in momentum of the working fluids as they pass through the engine installation. Thus:

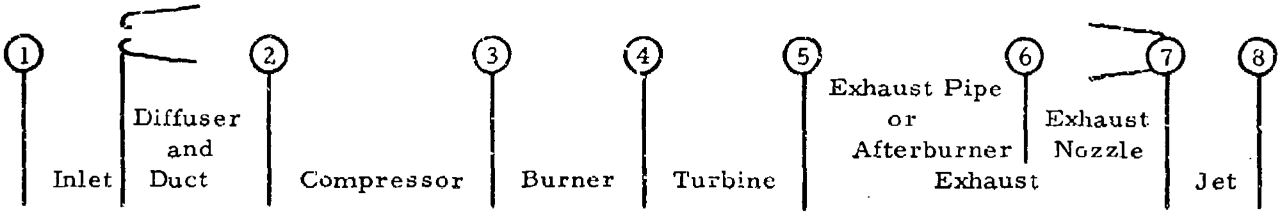
$$F_n = w_g V_8/G - w_a V_o/G$$

The above relationship may also be stated as follows: net thrust equals gross thrust ($w_g V_8/G$) minus ram drag ($w_a V_o/G$).

Ref. IV-6 "A Flight Thrustmeter for Turbo-Jet Engine," Schaevitz Engineering Technical Bulletin TR-100, November 27, 1961.

TABLE IV-2. DEFINITION OF TERMS

STATIONS



SYMBOLS

A	Cross-section area	in^2
C, K	Coefficient	
F, F_g, F_n .	Thrust, gross thrust, net thrust	lb
G	Acceleration due to gravity	ft/sec^2
k	Ratio of specific heats (c_p/c_v)	
m.........	Mass	Slug, $lb\text{-}sec^2/ft$
Pt, Pt6....	Total pressure	lb/in^2
R	Gas constant	ft-lb/lb-^oF
T, Tt6	Absolute total temperature Rankine, Kelvin	^oR, ^oK
v	Specific volume	ft^3/lb
V	Velocity, airspeed	ft/sec
w	Weight rate of flow (w_a)	lb/sec, lb/hr
Δ (Delta) .	Finite difference (Δ p)	

SUBSCRIPTS

a	Air (w_a)
am	Ambient (P_{am})
cr	Critical (F_{cr})
g	Gas (w_g), Gross (F_g)
n	Net (F_n)
o	Standard sea level, $T_o = 518.4^oR$, P_o = 29.92 in Hg, V_o = velocity, air speed
t	Total (Stagnation) ($P_{t}6$)
1, 2, 3 ..	Stations as shown on above sketch

When there is no forward speed ($V_o = 0$), the net thrust is equal to the gross thrust. The gross thrust of a turbo-jet installation can be determined easily and accurately on the ground by means of a thrust cradle which measures the forward force on the installation.

In this brief summary, no attempt will be made to develop the relationships here stated:

For P_{am}/P_{t6} numerically greater than critical (sub-critical flow),

$$F_g = 7.97\,K\,A_7\,P_{t6}\left[\left(\frac{P_{am}}{P_{t6}}\right) \quad - \quad \left(\frac{P_{am}}{P_{t6}}\right)\right]^{0.749} \tag{1}$$

For P_{am}/P_{t6} numerically less than critical (critical flow),

$$F_g = 1.901\,K\,A_7\,P_{t6}\sqrt{1 - \left(\frac{P_{am}}{P_{t6}}\right)^{0.2509}} \tag{2}$$

At critical pressure, both equations yield the same result. For K = 1.335 (an average value of the ratio of specific heats), the critical pressure ratio is $P_{am}/P_{t6} = 0.539$.

Equations (1) and (2) can be used to calculate a thrust, given values for the variables P_{am}, and A_7. The value for P_{t6} can be obtained from the engine by means of a pressure probe or a rake inserted in the flow path. The value for P_{am} can be obtained from a tee connection in the altimeter line. The value for A_7 can be determined by physically measuring the diameter of the outlet of the engine exhause nozzle. Actually, the values thus obtained will not be the effective values because (1) the efficiency of the pressure probe or rake will not be 100%, (2) the gas expansion results in a vena contracta of the jet thus realizing a different effective area than the one measured, and (3) minor variations affect the ratio of specific heats, k.

If the actual gross thrust is determined by static operation on a thrust cradle and divided by the theoretical thrust as determined by the above formulas, the ratio will be a thrust coefficient or calibration factor represented by K in equations (1) and (2). Once the value of K has been determined, it can be set into the Thrustmeter by means of a simple adjustment in order to yield correct readings.

The thrust coefficient remains sensibly constant over the operating range for any one type of installation. Its value is usually somewhat less than 1.

The relationships defined by equations (1) and (2) have been plotted in figure IV-26. In plotting the curves, both sides of the equations have been divided by $K\ A_7\ P_{t6}$. The theoretical engine performance is represented by a composite curve consisting of the dotted curve (subcritical) to the left of the critical pressure ratio and the solid curve (super-critical) to the right.

It may be seen that the super-critical formula, if extended to the left as indicated by the solid curve ABC, closely approaches the composite curve A'BC within the pressure-ratio range of 0.3 to 0.7.

The range of values of the pressure ratio P_{am}/P_{t6} between 0.3 and 0.6 (and to a lesser extent between 0.6 and 0.7) represents the region of engine operation in which a knowledge of the thrust value is of greatest interest. The region beyond 0.3 represents power and flight speed beyond the usual capability of the engine and air-frame, while the region beyond 0.7 represents idling and low-power operation well below normal flight conditions.

The Thrustmeter may be adjusted to follow either curve ABC or A'BC, whichever is desired, A'BC being slightly more accurate.

Simplified Formula

Equation (2) may be simplified by a straight-line approximately between the normal working limits of pressure ratio 0.3 to 0.7 with very little loss in accuracy (0.35% at the point of maximum deviation) to the form

$$F_g = 1.278\ K\ A_7\ (P_{t6} - 0.808\ P_{am}) \qquad (3)$$

This equation is comparatively easy to mechanize.

Since the engine area is a constant and known value, the equation may be further simplified to

$$F_g = K' \, (P_{t6} - 0.808 \, P_{am})$$

$$\text{where } K' = 1.278 \, K \, A_7 \qquad (3a)$$

Limits of operation for a particular engine are shown in figure IV-27.

One of the primary advantages of the straight-line approximation is the extremely simple computer design which is made possible. The computer requires no vacuum tubes (excluding the indicator servo-amplifier, which is physically located in the computer) and no moving parts (the pressure-sensing elements are not considered moving parts in the usual sense). The calibration can be expected to remain stable indefinitely. By virtue of the design, the readings are insensitive to acceleration and to variations in line voltage, frequency, and temperature.

Another important advantage is the flexibility of the straight-line computer compared with any computer that might be designed to solve the thrust equation "exactly". For example, if the ratio of specific heats should be found to differ from the value assumed in deriving equation (2), the effect would be to change the coefficient 1.901 and the exponent 0.2509. A computer design based on the exact formula would probably be unable, without considerable complexity, to adjust for different values of this exponent. However, a straight-line approximation can be fitted quite closely for any exponent over a considerable range of values. Referring to equation (4), the effect of a change in exponent would be to change the coefficients 1.278 and 0.808 in order to get the best fit between the straight line and the curve. Adjustments for this propose are available in the Schaevitz Thrustmeter; although normally factory adjustments, they may be altered as required. Similarly, an adjustment is provided for setting in the correct value of K A_7, which must be determined by test.

As pointed out above, some theoretical improvement in accuracy would be obtained by following curve A'BC rather than ABC in figure IV-26. Since A'BC is a composite curve, the sections of which obey different equations, the "exact" mechanization of this curve might be even more complex than the mechanization of either equation alone. Here again the flexibility of the straight-line method is a great advantage. By means

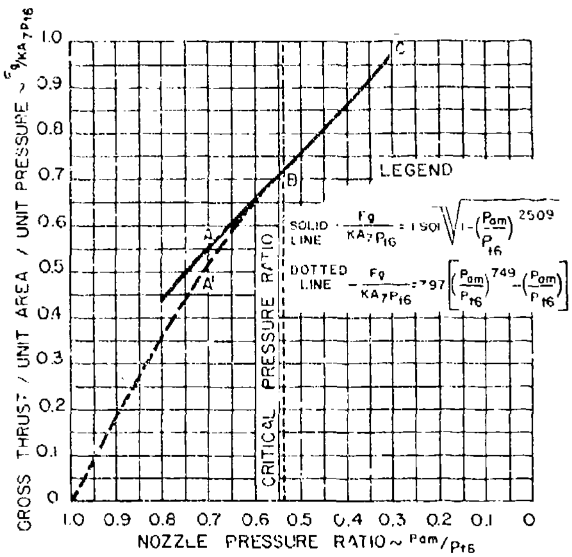


Fig. IV-26 Gross Thrust vs Nozzle Pressure Ratio

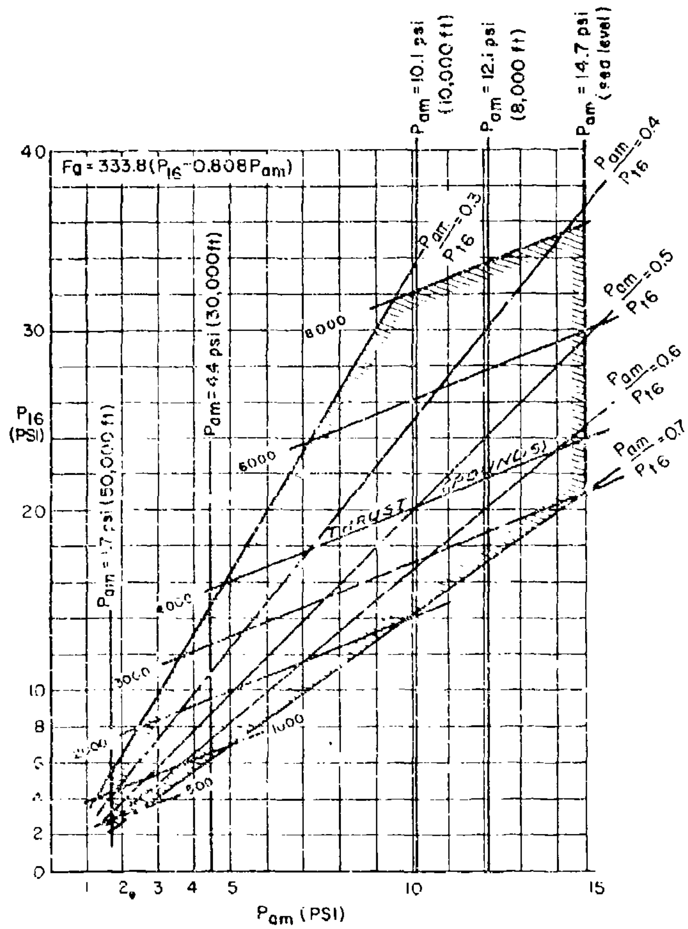


Fig. IV-27 Straight-Line Formula, Thrust and Pressure Relationships

of adjustments provided in the Thrustmeter, a straight line could be fitted to the composite curve A'BC if desired instead of ABC. In this case, if the line were fitted to keep the deviation at the upper end within 0.5% of full scale, there would be some loss of accuracy at the lower end. Down to a pressure ratio of 0.66 the deviation would still be below 0.5%, but it would reach 1.2% at a pressure ratio of 0.7.

Any discussion about matching the theoretical curves within a fraction of 1% is probably academic, for while the Thrustmeter itself is capable of such accuracy, the actual engine performance curves may differ somewhat from the theoretical curves of figure IV-26 because of minor differences between the nominal and the actual parameters. Available data, however, indicate that actual engine curves, if they do not exactly conform to the curves of figure IV-26, are at least of the same form, and in particular, that they can be closely approximated by straight lines.

For the reasons given above, it is believed that the Thrustmeter based on a straight-line approximation will prove to give more accurate, stable, and reliable operation, and to be simpler, yet more versatile, in calibration than a thrustmeter which attempts to solve the thrust formula exactly.

MECHANIZATION

Remembering that all pressure values in equation (3) are in absolute units, the equation can be written

$$F_g = (P_{t6} - P_a) - 0.808 \; (P_{am} - P_a) - 0.192 \; (0 - P_a) \qquad (4)$$

Three Bourdon tubes are used, one connected to the rake measuring $(P_{t6} - P_a)$. The second, connected to a source of ambient pressure, measures $P_{am} - P_a$; the third, which is evacuated and sealed, measures $0 - P_a$ or simply P_a. It will be noted that P_a may differ from P_{am} since P_a represents the pressure surrounding the Bourdon tubes and P_{am} is the pressure outside the aircraft.

Measurement of the Bourdon tube tips is accomplished using Schaevitz Linear Variable Differential Transformers (LVDT's). The outputs of the three LVDT's are connected into adjustable voltage divider networks, the P_{am} unit being reduced in the ratio 0.808 and the vacuum LVDT in the ratio of 0.192 compared with the P_{t6}. These settings correspond to the coefficients in equation (4).

The outputs of the LVDT's are closely phase matched, causing the outputs to combine algebraically when connected in series. Negative signs are represented by opposite phase. In this manner, a voltage is produced which changes proportionally to gross thrust. A fourth LVDT is added in series, its core position being manually adjustable so as to concel out any bias voltage resulting in a net output accurately proportional to gross thrust.

4. Bio-Instrumentation (Ref. IV-7)

The School of Aerospace Medicine at San Antonio has the greatest experience and the most advanced approach in terms of flight instrumentation for blood pressure measurement. They have two instrumented F-100 aircraft in which blood pressure records can be taken during flight. One of their units has been flown in a TF-102 at the AFFTC, Edwards Air Force Base. The instruments are individually made by the shop at SAM. A great deal of de-bugging and reliability work has gone into the current devices. They are small enough to be included in a seat kit, which also contains other physiological transducers. The information is telemetered during flight. Limitations have to do with the fixed nature of the blood pressure program; a cam repeats the cuff inflation cycle at any chosen time interval, depending on the cam used and the rate of drive of the motor. The system could be further miniaturized. The device is particularly adapted to usage in fighter aircraft.

Ames Research Center at Moffett Field, California, has constructed a device derived from the SAM design, with certain improvements in mechanical features, layout, and packaging. The development is based in part on the flight experience at Edwards Air Force Base with the early SAM unit. Plans for further improvement were initiated by submitting the design to Datalab Division of Consolidated Electrodynamics Corporation for critical appraisal and recommendations for reducing bulk and increasing reliability, safety, and signal strength. The present device is significantly affected by acoustic noise in the environment and by movement, the weakest element being the microphone, an inexpensive, small hearing aid device. While it has been successfully used on the centrifuge and in flight (at least sevel flights in the T-33, eight in the F-104B), it does not appear suitable for space vehicle usage in its present form.

At AiResearch, a demonstrator model has been made. Its particular advantage is that the method appears to be, of any seen, the least affected by noise in the environment and movement on the part of the subject. This is achieved through the use of a special broad surface contact microphone which is quite directional -- that is, it ignores inputs from the back of the housing. Finally, the signal from the microphone is passed through a very narrow band pass filter centered at 35 cps. This frequency probably represents a harmonic for the basic resonant frequency in the arterial system. Body motions, such as a circular motion of the forearm, do not obscure the pulse signal, although the pressure trace is, of course, affected. External noise fields affect it

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Ref. IV-7 Same as Ref. 236

very little. Special adaptation of this device to the Mercury capsule is presently under way, the company being already familiar with installation restrictions.

Wright Air Development Division has a device made by the Systems Research Laboratories of Dayton for monitoring subjects under various kinds of experimental stress. This is the Cadillac of automatic blood pressure devices. An electronic computer-programmer which controls cuff inflation causes the cuff to inflate up to the diastolic pressure, detect diastolic pressure, confirm it by insisting on coincidence of arterial sound with puffs of air from the cuff, waits for a confirming second sound and cuff puff, then rapidly inflates and searches for systollic pressure in the same way. The readout of the device is in terms of the two pressures, systollic and diastolic. The device is strictly a laboratory unit in its presnet form. It is presently in use in water flotation studies in the Biophysics Branch.

Systems Research Laboratories of Dayton, which made the WADD device, has just completed a miniaturized and transistorized, self-contained unit for field use, for the Civil Aeromedical Research Institute (CARI) of the Federal Aviation Agency, Oklahoma City. The device is identical in operation to the one made for WADD, but it contains its own small gas bottle supply and a telemetering transmitter, all packaged neatly in a box measuring approximately 10 x 12 x 3 inches. The weight of the unit is approximately 10 pounds. This device has been built for a specific purpose, so that certain other features -- for example, flexibility of program -- are limited for space applications. However, the basic instrument is extremely adaptable to any situation. Limitations include inexperience of this company with missile hardware, and limited experience with getting rid of movement and noise artifacts.

In summary, the device most nearly ready and suitable is that offe d by AiResearch. The experience at the School of Aerospace Medicine and . mes is valuable and pertinent. The device made by Systems Research Laboratories is perhaps the most attractive from the data-handling and programming standpoint.

PRESSURE TRANSDUCER EVALUATION PROCEDURE(GENERAL)

1. Scope - This procedure will be used in evaluating pressure sensing transducers at DRP, Edwards AFB.

2. Test Equipment and Procedure

2.1 Test Equipment

2.1.1 The output voltages in the range of 0 to 1.4 volt will be measured with a Leeds and Northrop K3 Potentiometer. This system will provide an accuracy of ± 0.05% of the reading.

2.1.2 Output voltages in the range of 1.4 volt to 5 volts (D. C.) will be measured with a John Fluke Company Model 801A differential voltmeter.

2.1.3 Any D. C. supply input voltage will be monitored during all testing by a J. Fluke Company Model 801A differential voltmeter.

2.1.4 Pressures will be provided by an oil deadweight tester in the 100 to 5000 psi range, while pressures up to 100 psi will be measured by means of an electro-manometer or air deadweight tester, each capable of ±0.1% static accuracy or better.

2.1.5 The environmental temperatures applied to the transducer will be measured by a laboratory mercury thermometer. The environmental temperatures will be applied with a Statham temperature chamber.

2.1.6 Atmospheric pressure will be monitored with a recording barometer when absolute pressure transducers are tested.

2.1.7 A Tektronix Oscilloscope with appropriate plug-in unit (and auxiliary amplifier if needed) will be used in Section 5 to monitor the transducer output voltage.

2.2 Test and Data Procedures

2.2.1 The test procedures will be carried out with the utmost care and precision. Any deviation from the procedures must be approved by the Test Engineer and should be noted on the test data sheet.

2.2.2 All test equipment and power supplied will be activated and allowed to stabilize for at least 6 hours prior to making any measurements. The L & N K3 potentiometer and associated equipment should be connected and allowed to stabilize at least 15 hours before measurements are made.

2.2.3 The test data will be recorded in duplicate. The original copy will be submitted to the Test Engineer, while the duplicate will be kept by the Technician conducting the test.

2.2.4 The transducer manufacturer's name, model and serial number and range will be recorded on each data sheet. In each observation in Section 3, 4, 5, & 6 the input and output voltages of the transducer will be recorded. The pressure applied, date, time of day, and environmental temperature will be recorded for each observation made under Sections 3, 4, 5, and 6. The atmospheric pressure recording (2.1.6) will be included with the test data if an absolute pressure transducer is being tested.

3. Static Accuracy

3.1 Linearity and Hysteresis

3.1.1 The linearity and hysteresis of the pressure transducer will be checked by applying pressure in five (5) equal steps in the up-scale direction, increasing from zero to full range pressure, followed by five (5) equal steps in the downscale direction, decreasing from full range to zero pressure.

3.1.2 Step 3.1.1 will be done three (3) times.

3.1.3 The hysteresis at any point will be determined by the following expression:

$$\text{Percent Hysteresis} = \left[\frac{\text{Down scale output reading - upscale output reading}}{\text{Full range reading-zero reading (downscale)}}\right] \times 100$$

3.1.4 The percent non-linearity at a specific point will be determined by the following relationship:

$$\%\text{Non-linearity} = \left[\frac{\text{Output reading at the press. point (downscale)}}{\text{Full range output - output at zero press. (downscale)}} - \frac{\text{Input Pressure}}{\text{Full range press.}} \right] \times 100$$

The non-linearity will be calculated using the data points which decrease from full range to zero pressure in 3.2.1.

3.2 Effect of Supply Voltage Change

3.2.1 The supply voltage will be varied in 3% steps, two(2) above and two(2) below the rated supply voltage with full range pressure applied to the transducer. Repeat this series of measurement two times.

3.3.2 The results will be recorded along with the environmental temperature and time of day as per Section 2.2 for zero and full range pressure for each supply voltage step.

3.3 Functional Zero and Sensitivity Drift

3.3.1 Supply voltage will be applied to transducer and it will be allowed to stabilize for 15 minutes just prior to a 0 to 3.5 hour test period. During this stabilization period, the hydraulic system will be exercised and the measurement system tested.

3.3.2 At time zero, full scale pressure will be applied and approached from the down scale side. The pressure is relaxed and zero pressure is approached from the up-scale direction. Recordings as per Section 2.2 are made for the zero and full range pressure. Ambient temperature and supply voltage will be held constant throughout the test.

3.3.3 Step 3.3.2 is repeated every 15 minutes for the first 60 minutes and once every 30 minutes for the remaining 2.5 hour period.

4. Temperature Effects

4.1 Static Temperature Effects

4.1.1 The transducer will be subjected to 25°C steps of

temperature and allowing the transducer to "soak" for 90 minutes at each temperature. The 25°C steps will extend from room temperature to the extreme low and high operating temperature ratings specified by the manufacturer. When the transducer has stabilized at the particular temperature, full range pressures approached from downscale and zero pressure approached from upscale will be applied followed by an electrical unbalance resistor applied to the bridge of the transducer set for 80% of full range output voltage at room temperature (25°C). Data as per 2.2 will be recorded.

4.2 Dynamic Temperature Effects

4.2.1 The Temperature will be increased at the rate of 10 degrees C in a 5 minute period. This increase will continue until the maximum rated operating temperature has been reached. Zero pressure output reading approached from an up-scale direction and the full range pressure output reading approached from a down-scale direction will be recorded at 25°C intervals starting at room temperature (25°C) and extending to the upper temperature limit specified by the manufacturer. The data recordings specified in 2.2 will be made.

5. Vibration Effects

5.1 The transducer will be subjected to the following vibrations in a direction normal to its major axis with full supply voltage and atmospheric pressure applied.

Frequency (cps)	Force (G's)	Time (sec)
20	10	30
50	30	15
100	30	15
200	30	15
500	30	15
750	35	15
1000	35	10
1250	35	10
1500	35	10
2000	20	10

5.2 The output voltage of the transducer subjected to vibration will be monitored with auxiliary amplifier-oscilloscope combination with a combined vertical sensitivity as defined by the following equation.

$$\text{Vertical Sensitivity (v/cm).} \leq \left[\frac{\text{Full Range Transducer Output Voltage}}{\text{600 CM}}\right]$$

5.2.1 Data as per 2.2 will be recorded, along with observed peak to peak output voltage caused by the applied vibration.

6. Dynamic Accuracy

6.1 The following tests will be conducted on the Shock Tube.

6.1.1 Three "shots" will be made on the shock tube at the highest practical and/or reliable full range pressure. An oscilloscope photograph will be made of each shot. An AFFTC form 0-336 will be completed for each shot and the photograph attached.

6.1.2 The environmental temperature, transducer input voltage, and time of day will be recorded as per Section 2.2.

7. Dielectric Test

7.1 The resistance to ground or case of each lead at the connector both input and output, will be checked at a voltage of 50 volts. The resistance will be measured under laboratory environmental conditions at room temperature. The resistance of each lead and environmental temperature will be recorded.
Caution: Do not apply the 50 volts between any two pins of the transducer.

8. Special Tests

8.1 Special tests will be added to this procedure from time to time by the Testing Engineer to cover the special characteristics of certain pressure transducers.

USER'S COMMENTS

In the interest of providing future revisions to the Telemetry Transducer Handbook with improved technical content and usefulness to the reader, it is urged that the following questionnaire be completed and returned to the following:

Radiation Incorporated
Melbourne, Florida

Attn: Telemetry Transducer
Handbook Project

VOLUME I

Section I - Radio Telemetry Systems

The purpose of this section is to provide basic information and fundamental characteristics of the transmission systems used in overall telemetry systems. The discussion along with over 100 selected references attempts to describe the principle of operation of various techniques and present in general the considerations involved in the use of each technique.

- [ ] Sufficient basic information is presented.
- [ ] Recommend additional technical data be presented for those systems described in this section.
- [ ] Recommend the following systems be added in future revisions of the Handbook: ____________________
  ____
  ____
  ____
- [ ] Comments being sent in separate letter.
- [ ] No comment.

Section II - Transducer Fundamentals

This section attempts to present a discussion of basic fundamentals in the measurement of physical parameters, and how they are or may be used in the translation of the measurement to a usable signal as employed in telemetering systems.

☐ Technical coverage of types of measurements described in this section needs improvement, specifically, ____________________
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☐ Technical coverage of types of measurements presented is adequate, for my purposes.

☐ The following types of measurements and associated instrumentation should be included: __________
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☐ Comments being sent in separate letter.

☐ No comment.

Section III - Transducer Applications

In this section an attempt is made to present a few examples of overall instrumentation requirements encountered in tests and operational flight programs, general aspects in the selection of the instrumentation hardware, and associated application details of some devices.

☐ This section should include the following applications of telemetry transducers: ____________________
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☐ The following sources of information are suggested: ____________________
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☐ Will submit recommended data under separate cover.

☐ Comments being sent in separate letter.

☐ No comment.

Section IV - Testing and Calibration

The material presented in this section has been compiled from technical reports and manufacturer's bulletins solicited for inclusion in the Telemetry Transducer Handbook. The desire is to present information on the considerations involved and methods and techniques used to test and calibrate various transducer devices.

☐ This section should include testing and calibration techniques pertaining to the following transducer types: ______________________________

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☐ The following information sources are suggested:

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☐ Will submit recommended data under separate cover.

☐ Comments being sent in separate letter.

☐ No comment.

Section V - Testing and Calibration Facilities

The information presented in this section was obtained by solicitation, from testing laboratories, government agencies, transducer users and manufacturers.

☐ Recommend data be requested from ____________
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☐ Will submit data under separate cover.

Section VI - References

The original format of the handbook endeavored to cite all references both in footnotes at the bottom of the associated page and in a numerical-order-of-appearance listing in a Reference Section of the handbook. The large number of references pertaining mainly to suggested detailed discussions made footnoting unwieldy. A comment is desired as to the reader's preference on placement and usefulness of reference notations.

☐ Footnotes only are sufficient.

☐ A List of References only is sufficient.

☐ Both Footnotes and a List are desirable.

☐ List of References should appear at end of each section.

☐ Recommend the following improvements in denoting reference: ____________________
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____
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☐ Comments being sent in separate letter.

☐ No comments.

Section VII - Bibliography

- [ ] Recommended bibliographical material being submitted under separate cover.

- [ ] Index to Bibliography may be improved in the following manner: ______________________________

- [ ] Bibliography at end of each section is desired.

- [ ] Comments being sent in separate letter.

- [ ] No comment.

Appendix I - Telemetry Standards

- [ ] Comments being sent in separate letter.

- [ ] No comment.

- [ ] Telemetry Standards presentation could be improved by: ______________________________

- [ ] Recommended reference material to add to Telemetry Standards: ______________________________

Appendix II - Glossary of Telemetry Transducer Terms

- [ ] Comments being sent in separate letter.
- [ ] No comment.

Appendix III -

- [ ] Comments being sent in separate letter.
- [ ] No comment.

VOLUME II

Section I - Transducer Manufacturers

- [ ] Recommended changes and additions are being submitted in a separate letter.
- [ ] No comment.

Sections II and III - Non-Switching and Switching Transducers

- [ ] The following transducer types should be added in future revisions to this volume:______________
  ____
  ____
  ____
  ____
- [ ] Data sheet format is satisfactory.
- [ ] Specifications are too numerous and detailed, in the majority of data sheets.
- [ ] Recommendations being submitted in a separate letter.
- [ ] No comment.

Section IV - Drawings

Separation of drawings from data sheets:

☐ is not objectionable, ☐ is objectionable

☐ Comments being forwarded in a separate letter.

☐ No comment.

Section V - Research and Development Programs

☐ Format should be expanded to include the following information: ______________________________
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☐ Comments being forwarded in separate letter.

☐ No comment.

The above comments are presented from the following viewpoint:

☐ Engineering

☐ Engineering supervision

☐ Sales

☐ ______________________________

When available, revisions and supplementary handbook pages

☐ are desired

☐ are not desired.

Revisions and supplementary pages should be mailed to the following individual, who will be cognizant of the handbook's custody:

Name

Title

Company

Address

This questionnaire was completed by:

Name

Title

Company

Date